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AFAMRL-TR-80-123

AIRCREW WINDBLAST PROTECTION CONCEPTS, DEVELOPMENT AND EVALUATION

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MARCH 1982

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FOR THE COMMANDER

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AIR FORCE/56780/5 May 1982 — 150

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFAMRL-TR-80-123	2. GOVT ACCESSION NO. AD-A115 424	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AIRCREW WINDBLAST PROTECTION CONCEPTS, DEVELOPMENT AND EVALUATION		5. TYPE OF REPORT & PERIOD COVERED Final Report Oct 1979 to June 1980
		6. PERFORMING ORG. REPORT NUMBER NA-80-390
7. AUTHOR(s) R. J. Cummings W. J. Adams		8. CONTRACT OR GRANT NUMBER(s) F33615-79-C-0528
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rockwell International North American Aircraft Division P O Box 92098, Los Angeles CA 90009		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61101F & 62202F 7231/13/06 & 7231/13/10
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base OH 45433		12. REPORT DATE March 1982
		13. NUMBER OF PAGES 86
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Limb Flail Injury, Arm Restraints, Leg Restraints, ACES II Ejection Seat, Design Concepts, Test and Evaluation, Methods and Criteria

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The problem of protecting aircrews from limb injuries during high-speed ejection is addressed. Design criteria, data, and evaluation techniques that were developed to support the selection of an appropriate windblast protection device concept for the F-15 and F-16 fighter aircraft are described in detail. Several alternate arm and leg-restraint systems were designed, fabricated, and evaluated as part of the research effort. Test fixtures were designed and fabricated to simulate (1) cockpit geometry, (2) force relationships between

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (continued)

the seat and man, (3) deployment and retraction of restraints in 0.1 second, and (4) seat/man separation dynamics. The evaluation of restraint concept performance using the prototypes, evaluation plan, and test fixtures is described. The selection criteria to identify the best restraint designs are presented. A test and evaluation plan for airworthiness verification is described to aid follow-on engineering development efforts.

PREFACE

This is the final report for research contract F33615-79-C-0528. The research was accomplished by the North American Aircraft Division (NAAD) of Rockwell International (Rockwell), Los Angeles, California 90245. William J. Adams was the program manager and Robert J. Cummings was the principal investigator.

The Air Force technical monitor was James W. Brinkley of the Biomechanical Protection Branch, Biodynamics and Bioengineering Division, Air Force Aerospace Medical Research Laboratory (AFAMRL), Wright-Patterson AFB (WPAFB), Ohio.

This research was accomplished to develop aeromedical design criteria and evaluation methodology to support the design and development of equipment to protect aircrews against the windblast-induced limb injury during high-speed escape operations from the F-15 and F-16 fighter aircraft. The effort was organized to provide a foundation for subsequent engineering development efforts that will be accomplished by the Life Support Program Office of the Aeronautical Systems Division.

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SUMMARY

This research effort encompassed: (1) exploratory development of new windblast protection techniques, (2) demonstration of protective equipment concepts by laboratory tests, and (3) the development of aeromedical design criteria and evaluation techniques for windblast protective systems. To ensure applicability of the results of this research effort, the ACES-II ejection seat was used as the baseline seat design and the windlbast protective systems were required to be compatible with the cockpit installation requirements of the F-15 and F-16 and their two-seat configurations. This research effort was based on the windblast protection design criteria and constraints developed under Air Force Contract F33615-78-C-0514 (Cummings et al., 1979).

The approach consisted of six tasks:

1. Develop several alternative restraint strategies, using nylon straps, fabrics and nets,and build prototypes.
2. Develop a plan for evaluating the restraint prototypes against appropriate performance requirements, especially biomechanical performance.
3. Design and build test fixtures for simulating: (a) cockpit geometry, (b) force relationships between the seat and man, (c) deployment and retraction of restraints in 0.1 sec, and (d) seat/man separation dynamics.
4. Evaluate restraint concept performance using the prototypes, evaluation plan, and the test fixtures.
5. Identify the best candidate restraint designs.
6. Prepare a plan for airworthiness vertification for any limb restraint system.

Of the concepts designed or modified in Task 1 of this program, the best performing are the net-epaulet concept and the G-suit modification. In the net-epaulet concept, a passive lateral restraint net is deployed by an active retracting strap loop which breaks out of an epaulet-like keeper on the shoulder and is drawn down over the forearm and thigh. In the G-suit modification, load spreading devices are sewn to the backside of the thigh and calf sections of the garment. During ingress, a retraction strap is attached to these devices so that after strap retraction the legs will be held within the upper and lower leg guards.

Three other arm restraint concepts were evaluated. The first is a bent arm's-length sleeve which is donned on ingress. At deployment, a strap loop through the sleeve is pulled forward so that the sleeve supports the flexed arm like a tubular hammock.

The second concept employs an active wrist collar donned at ingress. The collar is connected to the seat by a loop of strap which passes through a ring at the lap belt buckle. The strap loop, in turn, is suspended over the shoulder by a ring and a small shock cord which serves as a slack control system. A second loop of strap also runs from the belt buckle ring over the shoulder to the seat back. This loop is guided laterally off the shoulder by

a spring wand during deployment. As this loop contracts, it pulls the upper arm against the torso while the collar pulls the wrist to the belt buckle ring.

The third concept is a deployable sleeve. The sleeve is stowed in a circular keeper which the seat occupant slips up his arm to the shoulder during ingress. During ejection, the sleeve is automatically deployed up and down the arm by one retracting strap running to the initiator area. A ring attached to a second releaseable strap provides a load path over the shoulder to the headrest.

One alternative leg restraint concept was also evaluated. This concept employs separate leg straps for upper and lower leg restraint. The upper strap requries donning at ingress; the lower strap does not. During flight, the upper leg strap is positioned over the thigh near the hip to minimize encumbrance. The lower leg strap is routed over the perimeter of the leg-well away from the occupant's body. During ejection, a spring wand lifts the thigh strap over the G-suit thigh bladder and then down over the upper leg near the knee. The lower leg strap is pulled off the leg-well opening and is drawn down to hold the calves within the lateral leg guards.

The product of Task 2 describes a series of tests, each of which contributes data to support one or more of a list of separate performance requirement evaluations. Eleven specific windblast protection system performance evaluations are defined:

1. Biomechanical loading of the limb joints and spine during escape.
2. Deployment dynamics and failure modes.
3. Deployment in windblast.
4. Release at seat/man separation.
5. Deployment and protection with adverse torso position.
6. Restriction of movement within the primary restraints.
7. Release for emergency ground egress.
8. Post-deployment access to the restraint emergency release handle.
9. Probable crew response regarding encumbrance.
10. Ingress/donning and doffing/egress.
11. D-ring and/or side-arm initiator compatibility.

Candidate designs are run through a series of seven tests using four specially designed test fixtures to provide the data for these evaluations.

In Task 3, the design goal was to provide the evaluator with the ability to inexpensively subject the candidate protection devices to a spectrum of adverse environmental conditions. The strategy behind the test fixture designs was to avoid the high cost of discovering design faults during rocket sled tests by building several low-cost test fixtures which could assist the evaluator in anticipating the likely response of a windblast protection system design to the complex dynamic environment of emergency escape. Accordingly, the potential measurement capability of the fixtures was generally traded for

functional capability. This decision was based on the assumption that a broad functional capability had a better cost/effect for the purpose of design fault identification than a cost-constrained, narrow measurement capability. In use, the test fixtures were successful in that they efficiently helped reveal many design faults in each candidate design tested.

The concept evaluations conducted under Task 4 produced a comprehensive picture of the overall performance of each concept. In particular, the performance trade-offs inherent in each concept, but not necessarily obvious, were revealed along with the relative merit which each concept gained or lost as a result of its performance trades. During Task 4, many design improvements for each of the candidate concepts were discovered and incorporated. The identificaiton of design faults and the discovery of improvements were greatly facilitated by using the test fixtures from Task 3. Part of the Task 4 product was 20 minutes of real-time and slow-motion films showing the candidate devices being subjected to the evaluation tests.

Task 5 involved summarizing and assessing the Task 4 results, presenting this assessment to the representative of the contracting agency and preparing this report and final drawings for the selected arm and leg restraint concepts.

A performance verification test plan for the concepts which are selected for Air Force use was prepared under Task 6. It is included in the appendix of this report.

The program flow chart is presented in Figure 1.

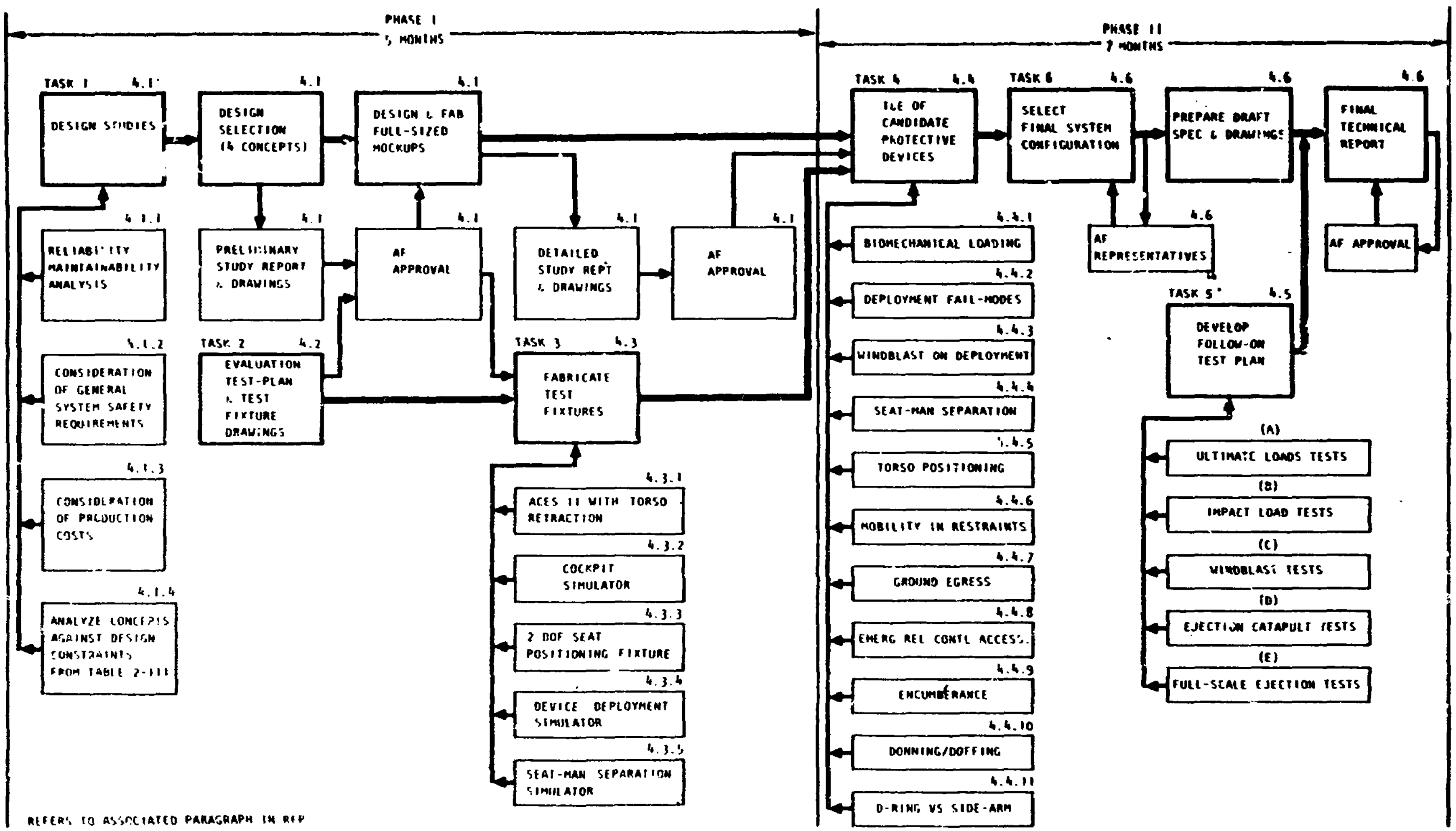

Figure 1. Program Flow Chart

INTRODUCTION

BACKGROUND

The problem of windblast induced injuries and fatalities during high-speed open seat ejections has been recognized for over 20 years and has been studied from a number of perspectives, including medical reviews of accident victims (Every et al., 1976; Belk, 1980), statistical summaries of ejection injuries (such as those presented at the NATO Advisory Group for Aerospace Research and Development Meeting in 1975), theoretical and wind tunnel aerodynamic studies (NATO/AGARD, 1975; Payne, 1974a; Payne, 1974b; Payne et al., 1975; Hawker et al., 1975; Hawker et al., 1976; Newhouse et al., 1978), anatomical studies (Fryer, 1961; Auffet et al., 1975; Grood et al., 1978), and numerous design programs, including new escape systems, ejection seat installations in new aircraft, and specific windblast protection devices studies (Phillips et al., 1973; Cummings et al., 1979; Stencel Engineering Corp., 1979). Despite this long and extensive effort, cost-effective hardware for providing limb flail protection to those who regularly fly in open-ejection-seat-equipped aircraft has yet to be widely accepted and implemented.

The difficulty of discovering a universal solution to the windblast injury problem is not surprising when consideration is given to the complexity of design constraints which arise from the following sources:

1. The escape environment.
2. Anatomical vulnerabilities of ejectees.
3. Structural and functional characteristics of the escape system.
4. Visual, control, and life support functions of the cockpit.
5. Crew requirements for mobility, restraint, external vision, physiological stress control, comfort, and appearance.
6. Command requirements for logistics, maintenance, justifiable cost/benefit.

The structure of this list of design constraint sources illustrates a two dimensional interpretation of the design requirement integration problem. First, the list shows a progression of scope of interest from narrow to broad. Second, each level of scope is represented by to or more technical disciplines The following list is representative of the number of different technical disciplines contributing requirements to the windblast protection problem: physics, aerodynamics, anatomy, biomechanics, impact dynamics, structural design, escape system design, protective equipment design, crew station design, human engineering, fighter piloting, operational test and evaluation (T&E), logistics, systems procurement, maintenance, pricing. The number of technical fields involved with this problem generate a large complex body of requirements and constraints, many of which are contradictory (Cummings et al., 1979). This makes discovery of a satisfactory solution very difficult and weighs in favor of carrying a variety of design approaches into the advanced development stage, where more funds are available to bring together the disciplines with the critical conflicting design requirements for resolutions and final design selection. The following pages present some background to the design problem from the perspectives of the six sources of design constraints listed above.

ESCAPE ENVIRONMENT

The elements of the escape environment pertinent to the windblast protection problem are: (1) aerodynamic pressure, (2) attitude instability, and (3) decelerator/stabilizer forces. At 600 KEAS the free stream dynamic pressure is approximately 1220 pounds per square foot. The aerodynamic forces acting on the limbs at this speed range up to about 500 pounds. In the absence of counteracting forces, these aerodynamic forces are capable of decelerating a loose arm or leg so much more rapidly than the torso/seat that injuriously high relative velocities between the limb and torso are reached. At 500 pounds force the probability of letting go of a side-arm or D-ring initiator is 100 percent (Horner et al., 1973). Therefore, windblast protection require that some means of applying forces to counteract excess aerodynamic loads on the arms be provided. On a stable seat, aerodynamic pressure bends the lower legs under the seat and lifts the upper legs. With the lower leg trapped under the seat pan, the lift forces on the upper leg must be carried by the knee joint as tension loads. Such tension loads are increased by drag forces acting on the feet and the uncounterbalanced inertial response loads of the upper part of the lower leg. The inertial load is caused by the front panel of the seat bucket which traps stagnated air behind the legs and thereby cancels the action of the aerodynamic pressure on the front of the legs. Windblast protection for the legs requires that the knees be relieved of the aerodynamic pressure induced tension load which they bear.

Attitude instability (weakness or absence of tendency to align with the flight path) in open ejection seats is well documented and understood (Payne, 1974a; Payne, 1974b; Payne et al., 1975; Hawker et al., 1975). A consequence of attitude instability is that aerodynamic forces may act on the arms and legs over a wide range of angles-of-attack. Windblast protection, therefore, requires that support against aerodynamic forces be available over a wide range of angles-of-attack as well.

Decelerator/stabilizer forces refer to the forces applied to the seat and man at drogue inflation. The drogue inflation event reverses the force relationship between the seat and man. Initially the seat is pushing the man. At drogue inflation the seat is pulling on the man through the shoulder straps and lap belt. This force reversal can result in relative movement between the seat and torso within the range of mobility allowed by the primary restraints. Arm and leg windblast protection requires that this motion be accommodated without passing drogue inflation forces through the torso to the limbs.

ANATOMICAL VULNERABILITIES

Payne (1974b) observed that limb flail injury does not occur when an arm or leg is dislodged from its normal position, but when its rearward motion with respect to the seat is stopped. This is true for the special case of limb flail injuries. However, once the decision is made to use limb restraint, a broader view must be adopted. Thus, for this program, the potential for windblast induced limb injury without flail was considered. This approach is clearly warranted since windblast injuries of the leg have been observed as a result of ejections from the F-4 aircraft where leg restraints are used (Belk, 1980; NATO/AGARD, 1975).

During a stable high-speed ejection, stagnation pressure between the thighs forces them upward and sideward into low-pressure regions above the thighs' upper and outer surfaces. The lower legs hook under the overhanging forward edge of the seat pan and are held there by drag and sideward acting pressure forces. This may cause tension forces in the ligaments of the knee joint. Other sources of tension loads for these ligaments are the inertial force of the lower leg in response to catapult and rocket acceleration, the inertial force of the lower leg in response to its impact with the lower seat bucket due to drag deceleration, the inertial resonse of the lower leg in response to drogue shock and possibly seat realignment, and torsion forces in the lower leg due to possible aerodynamic instability of flight boots. These baseline sources of tension loading in the knee ligaments can occur regardless of whether there is leg flail or not. The knee joint, therefore, may be loaded in tension and may suffer torsion during ejection.

Successful protection of the knee joint ligaments against strain injuries may be provided by downward restraint forces applied to the upper leg near the knee. The lower leg must be free to move upward in response to upward tension forces in the knee ligaments and must be restrained against movement forward and outward around the lower leg fence.

When exposed to 1,200 psf windblast conditions, unrestrained arms will flail violently. Ejection experience shows that this typically results in dislocations of the bones in the upper and lower arms. To prevent these injuries, arresting and restraining forces must be applied to the arms prior to hyperextension of the elbow or hyperrotation of the shoulder joint.

Successful protection of the ligaments in the shoulder and elbow joints from dislocation associated injuries may be provided by the application of forward and inward acting restraint forces on the lower portions of both the upper and lower arms.

Limb restraint designs that employ straps which are cinched down on top of the shoulders should probably be avoided (Stencel Engineering Corp., 1979). Such designs, particularly if cinched down during catapult stroke, may increase the risk of spinal injury during drogue shock by preloading the spinal column in compression.

ESCAPE SYSTEM STRUCTURE AND FUNCTION

An open ejection seat based on the requirements of MIL-S-9479B, the General Specification for USAF Aircraft Upward Ejection Seat Systems (1973), has only a few options for connecting limb restraint loads to seat structure. For the arms, the load paths and reaction point options include: (1) between the legs to the front of the seat pan, (2) to the lap belt, (3) to the forward seat sides, (4) to a tension line erected between the headrest and seat pan or forward seat sides, (5) to the sides of the seat back, (6) behind the back of the shoulders to the shoulder harness, and (7) around the back to the opposite side restraint. The leg restraint load reaction point options are: (1) the front of the seat bucket, (2) the forward section of the seat pan, (3) the center of the lap belt, and (4) the lower leg fences. Arm and leg restraint design approaches may incorporate one or more of these structural parts for load reaction.

The functional characteristics of the escape system in the context of their impact on arm and leg restraint designs were described elsewhere (Cummings et al., 1979). The ten phases of escape system operation pertinent to the windblast protection problems are:

1. Normal and combat operations, ingress/donning, doffing/egress, emergency egress.
2. System initiation.
3. Canopy jettison, pre-ejection positioning, windblast protection deployment.
4. Catapult initiation and stroke, sustainer and pitch trim thruster ignition.
5. Drogue projection, sustainer/CG pitch-yaw instability, drag center/CG pitch-yaw-roll instability.
6. Drogue shock.
7. Pitch-yaw damped oscillations, drogue deceleration, roll instability.
8. Main chute projection, pitch aft moments from main chute mortar, drogue drag, and riser drags.
9. Drogue release, restraint release (yaw due to aft pitch plus roll).
10. Main chute shock, seat/man separation.

COCKPIT INTEGRATION

A successful windblast protection design must be compatible with the design of the displays, controls, workspace, and life support provisions of the cockpit and with the cockpit/escape system interface.

The design of the protection devices must preserve the crew's baseline visual and manual access to the displays and controls. The baseline workspace provisions should not be reduced, for example, in the leg-wells or on the seat backsides behind the elbows. Catching of straps or lines on controls or other cockpit provisions must not occur. Protection devices must operate in the presence of arm rests, oxygen and anti-G garment supply lines, pencils in sleeve pockets, inflated anti-G garmet bladders, leg mounted clip boards, and bulky winter weight clothing. The design must fit in the spaces available. For example, the F-16 has minimal clearance (0.25 inch) along the side panels and a center console between the occupant's legs. Also, consideration must be given to the likelihood of the occupant's limbs being pressed against cockpit surfaces by aircraft accelerations sustained during ejection, that is, restraint designs should require free passage around the legs or arms.

CREW REQUIREMENTS

Fighter crews have a need for mobility within the cockpit, particularly to achieve maximum vision. New aircraft provide vision unparalleled by previous systems. Maintenance of this capability is partly quantifiable by mockup vision and reach studies with and without the restraint system in question, but with all other systems represented.

However, fighter crews must perform under extremely stressful conditions. What seems under normal conditions, small reductions in mobility, external

vision and comfort, or small increases in encumbrance and physiological stress due to a windblast protection design may, under combat maneuvering conditions, be amplified. For this reason successful windblast protection designs will be those which will not encumber the pilot under comabt maneuvering conditions.

Two subjective pilot reactions exist that present additional difficulty in demonstration and evaluation. First, although a given system design feature does not show up as a detriment during mockup studies, it may be preconceived as such by the pilot. This type of preconception is undoubtedly promoted by designs that either appear excessively complex or have a sufficient number of attachment points so that the pilot is constantly (or feels that he will be) aware of its presence. Given a design that is reasonably simple and an adequate training or introductory program, this problem is soluble.

The second subjective reaction will possibly pose a greater problem for some protection designs. Simply stated, the crewman often resists restraint, particularly of his hands and/or arms, as he feels he will be restricted controlling the aircraft especially if something should go wrong. This attitude has been observed in pilots even in relation to the catapult, rocket, and high-speed deceleration portions of the escape sequence when it is known that there is virtually no action they could perform in this time. This attitude is partially reinforced by two distinct possibilities. The first is the possible interference with the emergency seat/man separation initiator, which must be accounted for in the design. The second is the *a priori* assumption that an increase in the number of attachments to the seat increases the likelihood of failure of seat/man separation. Good design can provide some relief from this problem by combining attachments (if additional are required) to be released by existing functions. This problem may also require some form of awareness or education program to promote acceptance.

COMMAND REQUIREMENTS

Windblast protection designs must also meet the requirements of the various AF commands responsible for fighter aircraft weapons systems. These include operational system performance, logistics, maintenance, combat readiness, and cost/benefit justification. The ultimate acceptance of a windblast protection system will be greatly affected by its ability to meet these requirements. Because windblast protection systems have a history of poor crew acceptance, logistics commands will be reluctant to commit to procurement without adequate assurance of crew acceptibility by the command responsible for testing operational system performance. Using commands will be interested in maintainability and the potential impact on combat readiness. The procurement offices will be interested in the credibility of predictions for improvement in the rate of non-injury high speed escapes and shortened injury recovery periods. Finally, because there is a motivation to control weapons systems procurement costs by helping manufacturers reduce their liability for damages arising from ejection injuries, special attention is required to conduct and document adequate test and evaluation to assure that the final protection system performance will meet the operational need.

REPORT ORGANIZATION

The remainder of this report covers the results of the six tasks which made up the program. First, the initial design study is described. This study began

with the six windblast protection system concepts developed by the preceding program (Cummings et al., 1979). As a result of the design study, some concepts were abandoned, some were modified over a series of prototyping/redesign steps and some new concepts were incorporated in the program. Second, the development of four test fixtures is described. The fixtures were used to simulate cockpit geometry, restraint retraction, seat-man force relationships, and seat-man separation dynamics. Part of the development task was a trip to the Flight Test Center at Edwards AFB, California to study the cockpit/escape system interfaces of the F-15 and F-16 aircraft. Photographs of the cockpit interiors of these aircraft are presented with figures illustrating the designs of the four test fixtures. Third, the design evaluation plan for the candidate windblast protection designs is described. Fourth, the results of the test and evaluation of six concepts are presented. The first four evaluations are of derivatives of the original six concepts, and items 5 and 6 are new concepts added to the program, neither of which require specific attachment actions by the crew: (1) arm straps, (2) deployable sleeves, (3) leg straps, (4) G-suit leg restraint, (5) arm-length sleeve donned at ingress, and (6) net-epaulet arm restraint. Fifth, the selection process used to choose the overall best restraint concepts for the arms and legs is described, and the rationale for the selections made is given. Sixth, the appendix presents a proposed test and evaluation plan for arm and leg restraints.

WINDBLAST PROTECTION DEVICE STUDY

CONCEPT CONFIGURATIONS

The design study began with the six protection concepts recommended by the preceding program (Cummings et al., 1979). These concepts (shown in Figures 2 through 7) are labeled with Roman numerals to distinguish them from the designs which evolved from them (which are labeled with Arabic numerals 1 through 4). The original concepts were studied and evaluated for their performance relative to the design constraints listed in Table 1. This study led to the conclusion that concepts II and VI should be dropped from further development. Concept II was dropped because after deployment the circumference of the lower arm loops could increase at the expense of the upper arm loop so the lower arm could be forced back into hyperextension. Concept VI was dropped because the inflatable insert raised the thigh above the lateral restraint provided by the seat structure.

The remaining four concepts were developed through many iterations of the design-prototype-test process. The final designs are presented in the first four detailed design drawings listed in Table 2. Concepts 5 and 6 were added to the program under an extension of the original contract. They also were taken through many design iterations before arriving at the configurations in the Table 2 drawings. All six concepts were subjected to preliminary evaluations which concentrated on the area of weakest performance of each of concepts 1 through 6. From these preliminary evaluations it was concluded that Concept 2, a deployable sleeve, suffered from insoluble problems regarding its application of restraint forces to the arm. So Concept 2 was not subjected to the full performance evaluation. Similarly, Concept 3, deployable restraint straps for the legs, had an insoluble problem, a deployment failure mode. However, this fault was identified only after most of the full performance evaluation had been accomplished. Because of their faults, Concepts 2 and 3 are not illustrated in this report. Their problems are discussed in the section on evaluation results.

Of the remaining concepts, Concepts 1, 5 and 6 are for arm protection while Concept 4 is for leg protection. Figure 8 shows an intermediate design iteration for Concept 5 leading to the final iteration shown in Figure 9. The normal and deployed appearances and components of Concept 6 are illustrated in Figures 10 and 11.

TABLE 1. DESIGN CONSTRAINTS ON CANDIDATE CONCEPTS

Rank	Design constraint
1	Positive upper and lower arm and leg retention without tension or shear loading of the shoulder, elbow, or knee joints and without compression loading of the spinal column.
2	System deployment and active limb positioning are integrated with other body positioning and restraint mechanisms of the ejection seat and provide full protection prior to entry into the windstream.
3	No failure modes related to positive release at seat-man separation.
4	No failure modes related to adverse positioning of the limbs or torso, especially adverse positioning of the upper extremities.
5	Mobility within the primary restraint system after deployment.
6	Automatic sizing to accommodate full range (5th to 95th percentile) of crew size.
7	No failure modes related to entanglement on parachute landing or emergency ground egress.
8	Access to manual seat-man separation control, direct or indirect.
9	Psychological acceptability regarding encumbrance and appearance.
10	Producibility, maintainability, reliability, and safety.
11	Minimal donning and doffing tasks.
12	Compatibility with personal protection equipment.
13	Compatibility with either side-arm or D-ring controls.

TABLE 2. ARM AND LEG PROTECTION CONCEPTS

Concept No.	Name	Drawing No.
1	Arm straps	L9532773
2	Deployable sleeve	L9532774
3	Leg straps	L9532775
4	G-suit modification	L9532776
5	Arm-length sleeve	L9532777
6	Net/epaulet	L9532778

A sequence of photographs of each concept was taken to show their configurations in various phases of usage, such as pre-ingress, donning, reach, deployment and restraint. These photographs appear in the following groups of figures:

Concept 1 - Figures 12 through 17

Concept 4 - Figures 18 through 24

Concept 5 - Figures 25 through 30

Concept 6 - Figures 31 through 37

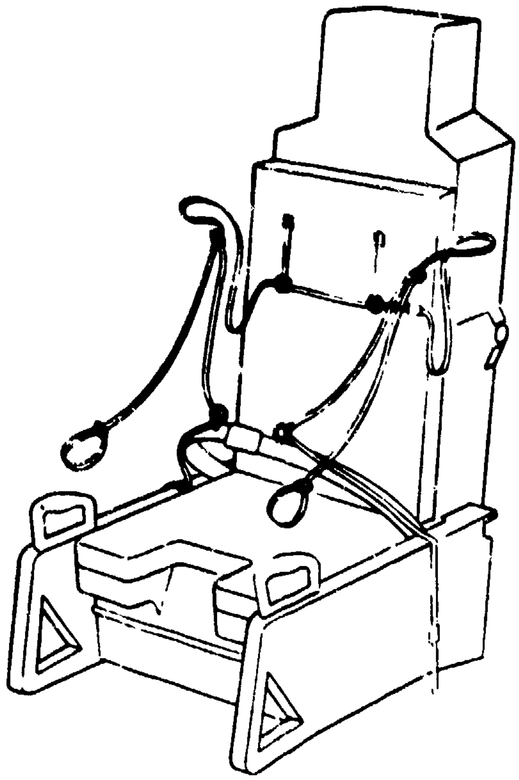

Figure 2. Concept I - Initial Arm-Strap Concept

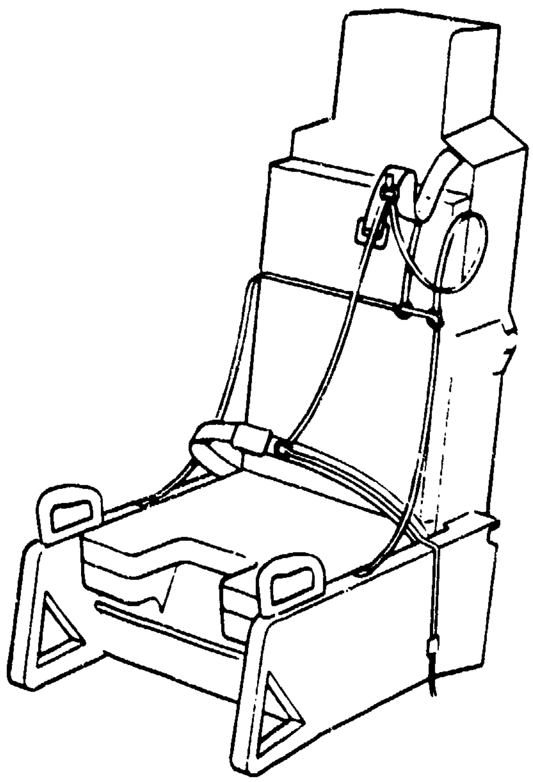

Figure 3. Concept II - Rejected Arm-Strap Concept

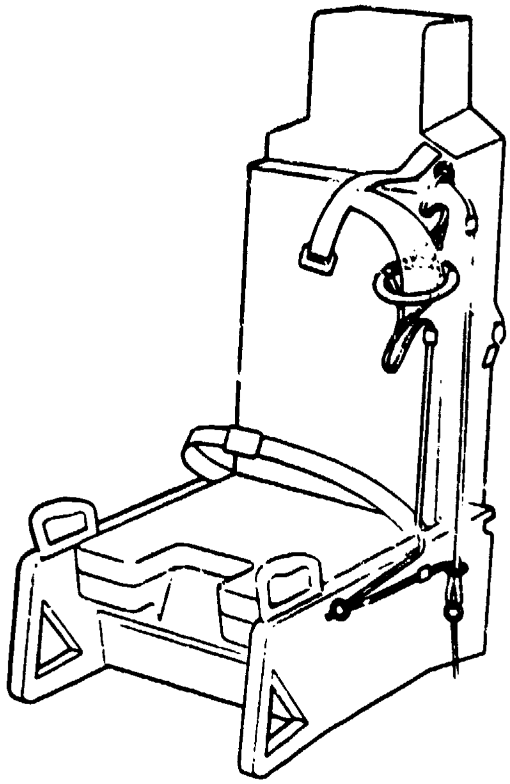

Figure 4. Concept III - Initial Deployable Sleeve Concept

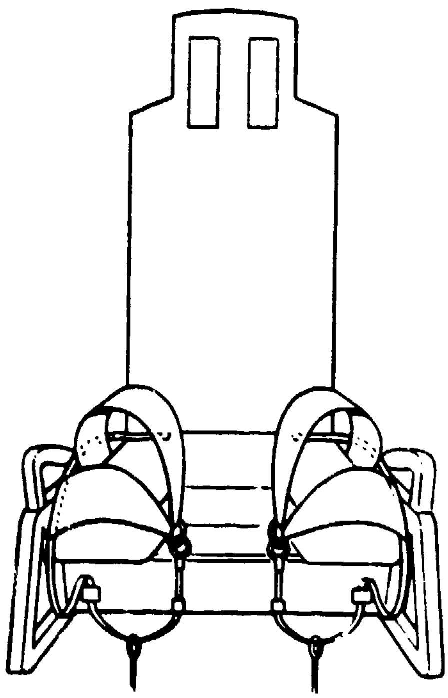

Figure 5. Concept IV - Initial Leg-Strap Concept

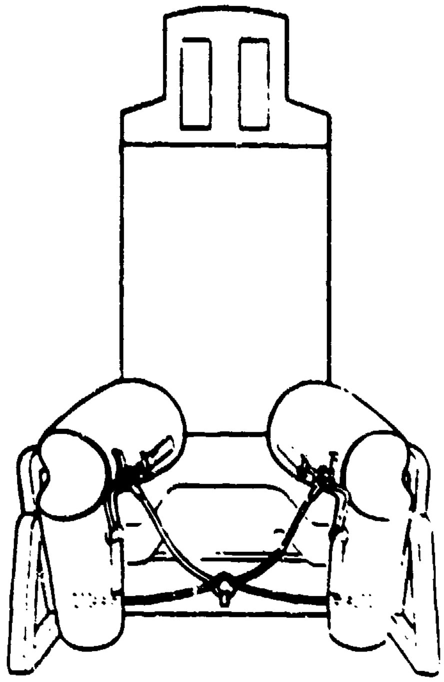

Figure 6. Concept V - Initial G-Suit Concept

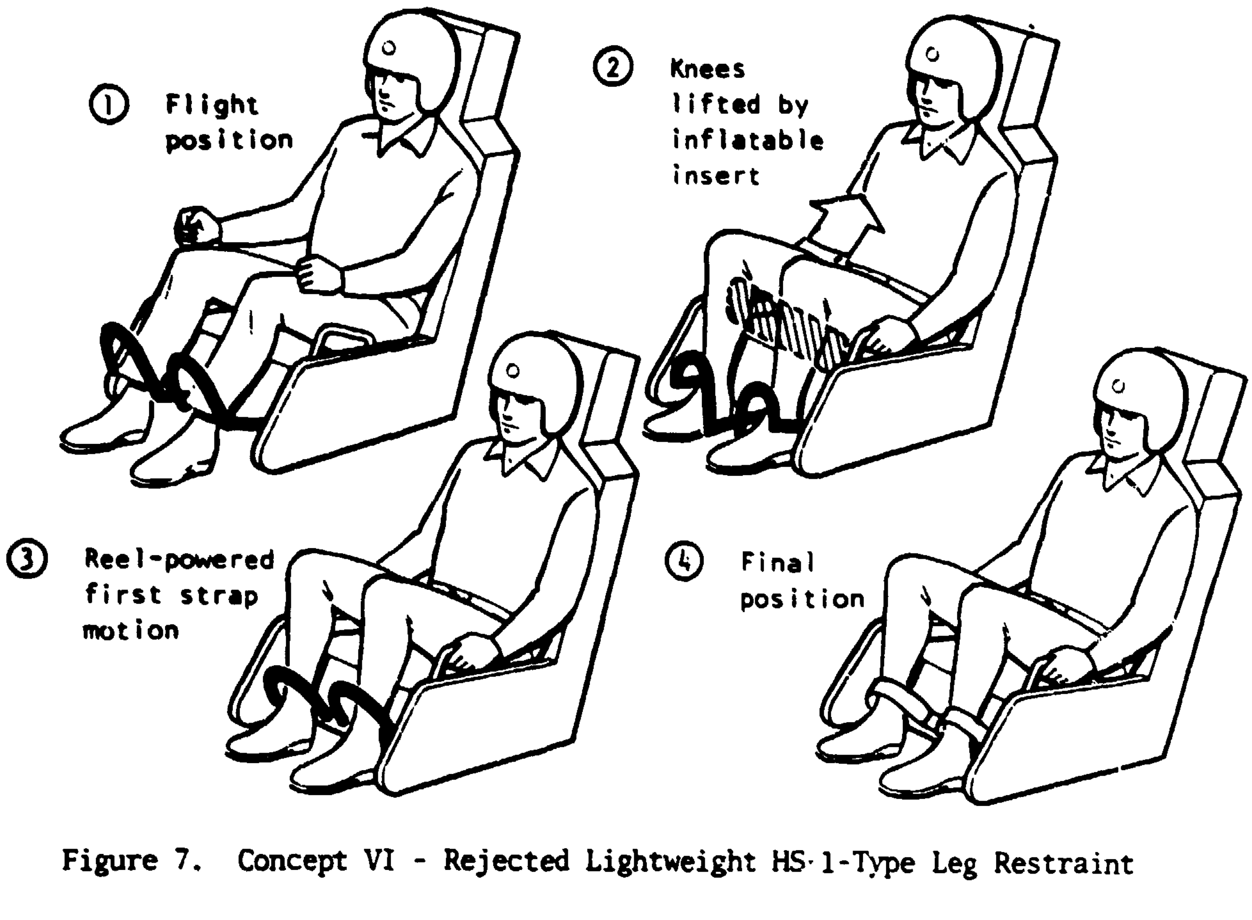

Figure 7. Concept VI - Rejected Lightweight HS-1-Type Leg Restraint

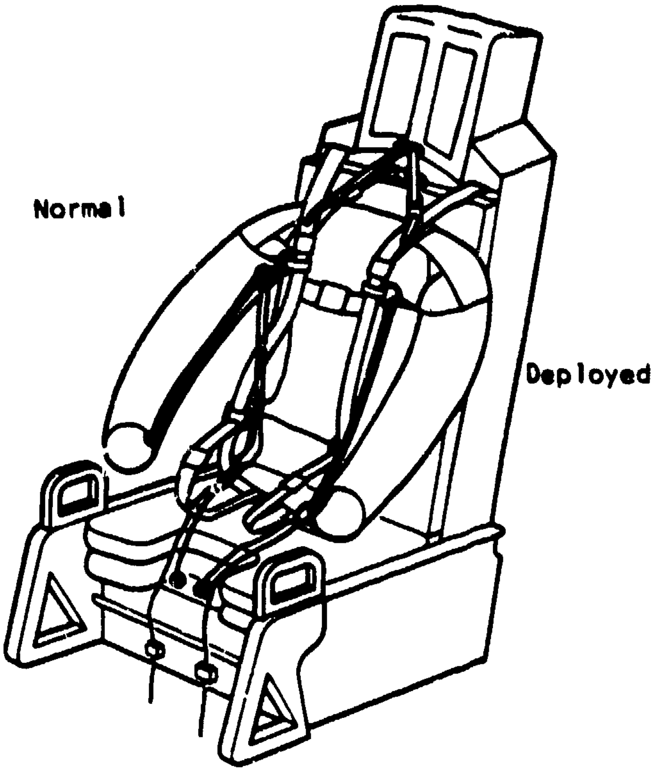

Figure 8. Arm-Length Sleeve Integrated With Parachute Harness

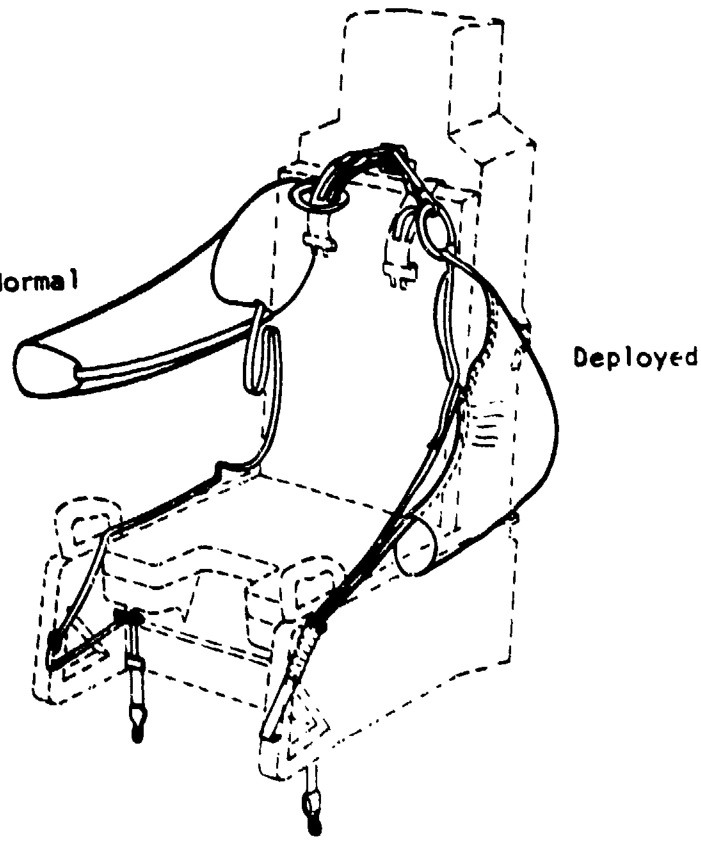

Figure 9. Arm-Length Sleeves Suspended From Shoulder Retraction Pulleys

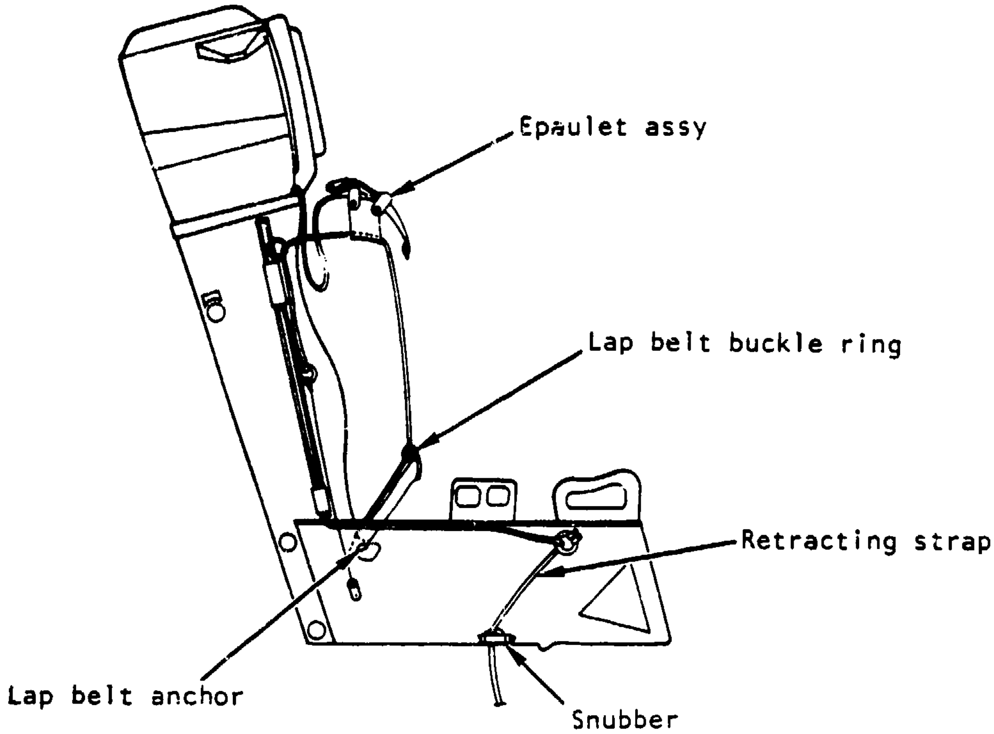

Figure 10. Net Epaulet Design - Stowed

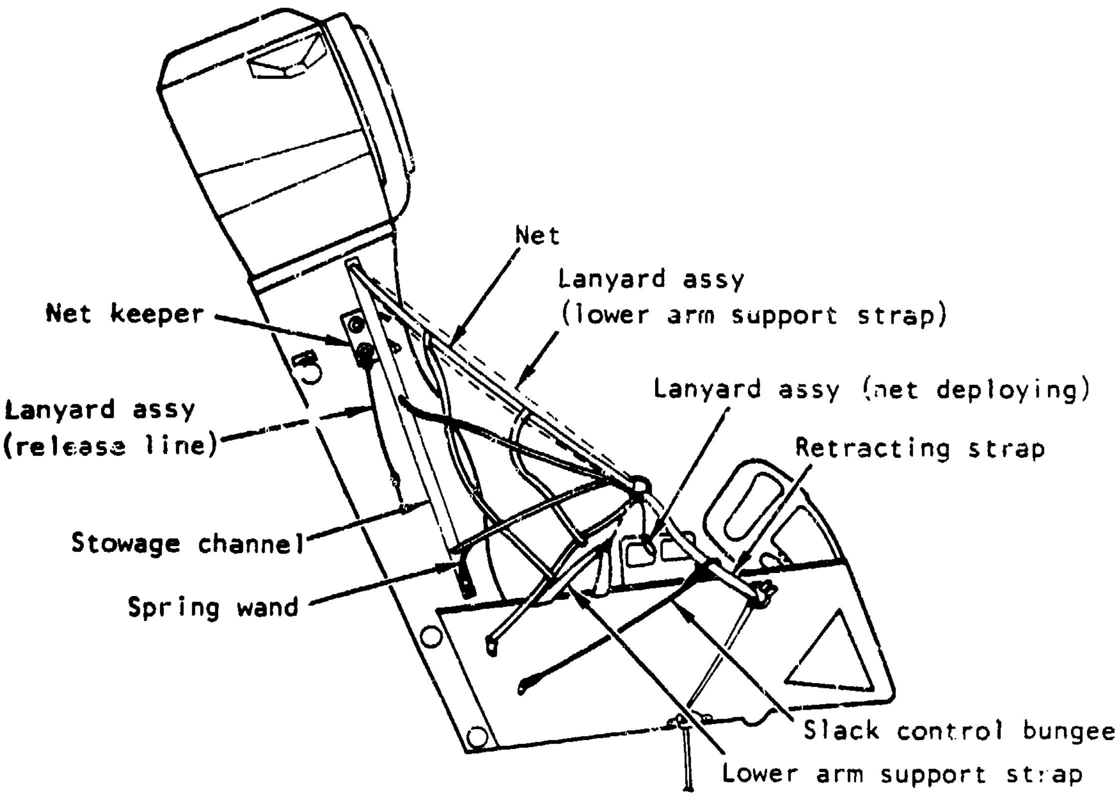

Figure 11. Net Epaulet Design - Deployed

Figure 12. Arm Straps - Preingress

Figure 14. Arms Straps - Showing Wrist Collar and Upper Arm Loop Above Shoulder

Figure 13. Arms Straps - Donning

Figure 15. Arm Straps - Showing Accommodation of Occupant Movements

Figure 16. Arm Straps - Half-Way Deployed

Figure 17. Arm Straps - Full Restraint

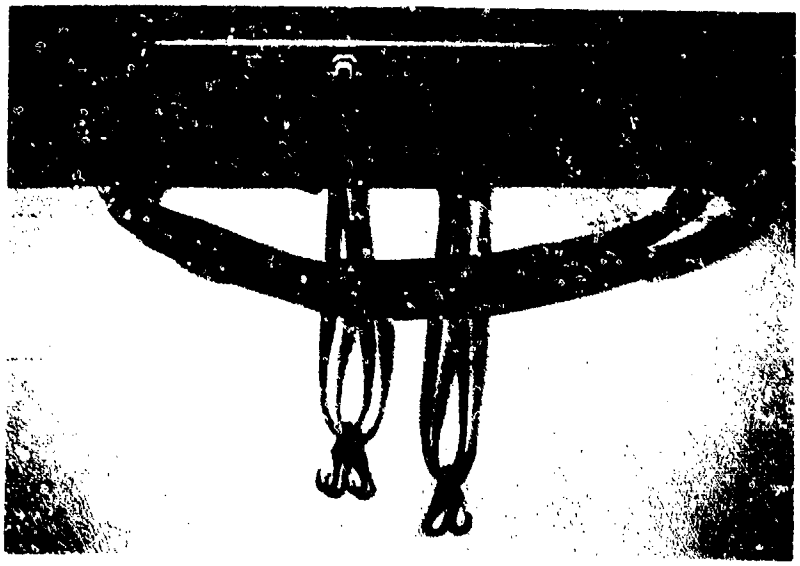

Figure 18. G-Suit Modification - Preingress

Figure 19. G-Suit Modification - Showing Snaphooks on Retraction Strap in Position for Donning

Figure 20. G-Suit Modification - Attaching Upper Leg Snaphook

Figure 21. G-Suit Modification - Attaching Lower Leg Snaphook

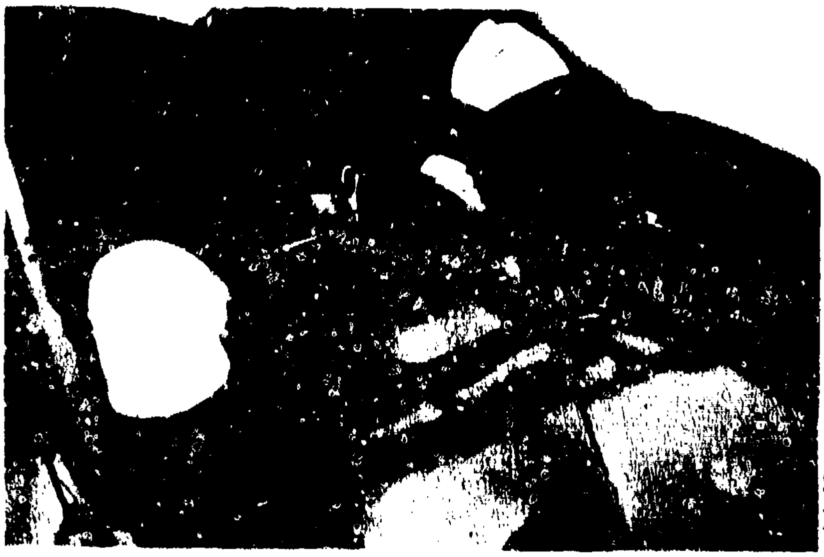

Figure 22. G-Suit Modification - Showing Accommodation of Leg Movements

Figure 23. G-Suit Modification - Deployed

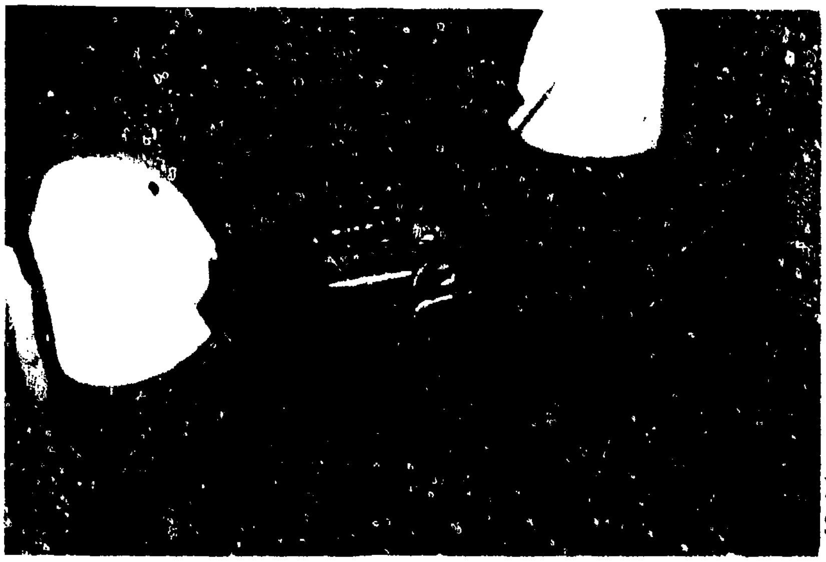

Figure 24. G-Suit Modification - Showing Ability of Lower Leg to Move up to Relieve Knee Ligament Strain

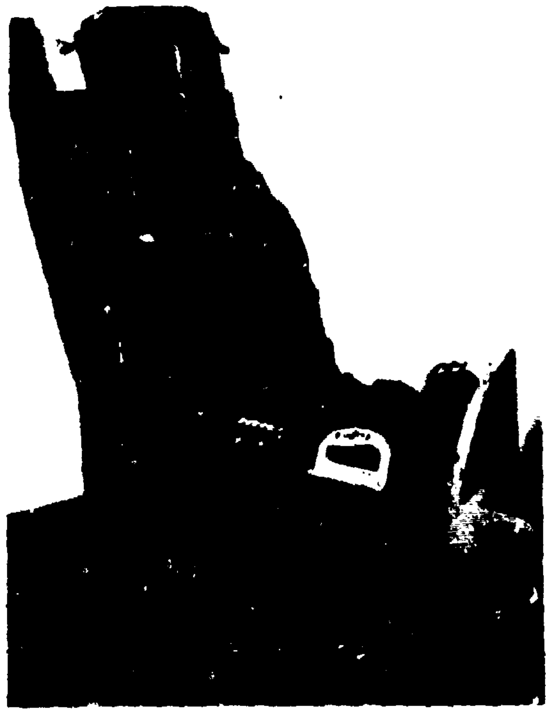

Figure 25. Sleeves - Preingress

Figure 27. Sleeves - Showing Conformity to Arms in Flight Control or Initiator Posture

Figure 26. Sleeves - Donning

Figure 28. Sleeves - Showing Accommodation of Occupant Movements

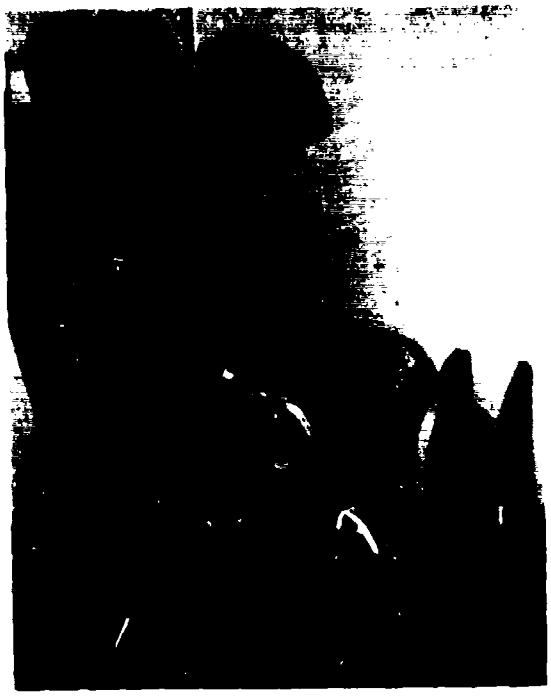

Figure 29. Sleeves - Deployed Showing Support of Arms on Initiators

Figure 30. Sleeves - Showing Arm Support After Grip on Initiator is Broken

Figure 31. Net-Epaulet - Preingress

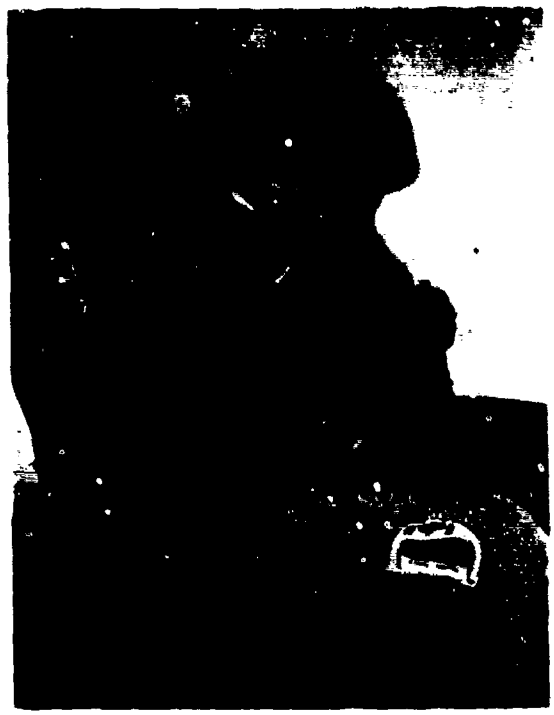

Figure 32. Net-Epaulet - Donning

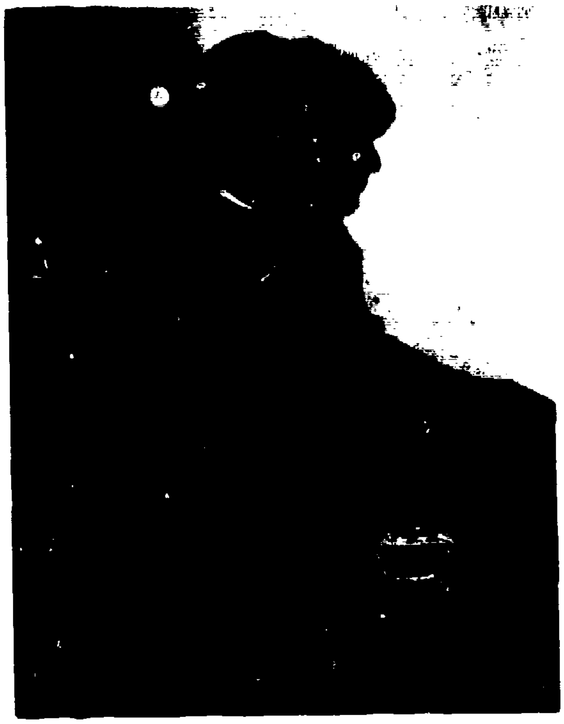

Figure 33. Net-Epaulet - Normal Use

Figure 34. Net-Epaulet - Showing Accommodation of Occupant Movements

Figure 35. Net-Epaulet - Half-Way Deployed

Figure 36. Net-Epaulet - Deployed Showing Support While Grip on Initiator is Intact

Figure 37. Net-Epaulet - Deployed Showing Support After Grip on Initiator is Broken

SIMULATORS FOR WINDBLAST PROTECTION DEVICE EVALUATION

An important area of investigation in this research was low-cost, special-purpose test fixtures. The test fixtures were developed to explore their ability to assist designers in the design and evaluation process. The program presumed that the numerous man-centered aspects of the windblast protection design problem would be relatively inaccessible to a designer if only conventional design tools such as 2-D manikins, upright attitude fit function checks, or low-speed deployment checks were used. A consequence of this inaccessibility could be that man-centered problems might show up too late in the design cycle. The program sought to demonstrate that the likelihood of discovering man-centered design problems at an early stage of the design process could be improved, if the designer were given access to a broader range of capabilities with which to assess the performance of his windblast protection concepts. Five strategies pertinent to man-centered design problems were identified:

1. Design test fixtures to simulate: cockpit free space, deployment dynamics, seat-man force relationships, and seat-man separation dynamics.
2. Design the operation of simulators to be inexpensive so that they may be used often; i.e., quick turnaround, non-destructive, safe one-man operation.
3. Encourage the designer to experiment with concept mockups before committing to detailed drawings.
4. Emphasize assessment of man-centered problems at the earliest possible time in concept development. Use low fidelity design mockups rather than waiting for production parts to be available.
5. As the first task in the concept development program, require the designer to study and describe the behavior of the baseline escape system in the environments simulated by the test fixtures.

These strategies are reflected in the designs of the following test fixtures designed and build for this program and delivered to AFAMRL:

1. Cockpit geometry (drawing L9532783).
2. Restraint retraction (drawing L9532780).
3. Seat-man force relation (drawing L9532781).
4. Seat-man separation dynamics (drawing L9532782).

COCKPIT GEOMETRY SIMULATOR

This simulator (Figure 38) is constructed of 3/4-inch plywood. Three adjustable panels on each side of the seat represent the canopy rail to side console, side console, and side console to floor panels. In addition, the flight controls, radar pedestal, 30-degree seat angle, and leg wells were simulated for the F-16. The flight control stick, windshield bow, 15-degree seat angle, and leg wells were simulated for the F-15. The simulator was used for demonstrations of ingress/donning, egress/doffing, normal mobility and encumbrance, emergency ground egress, and cockpit integration effectiveness. Figures 39 through 43 are photographs of the F-15 cockpit in a clockwise scan. Figures 44 through 48 are similar photographs of the F-16 cockpit.

Figure 38. Cockpit Geometry Simulator

Figure 39. F-15 Cockpit - Left Rear

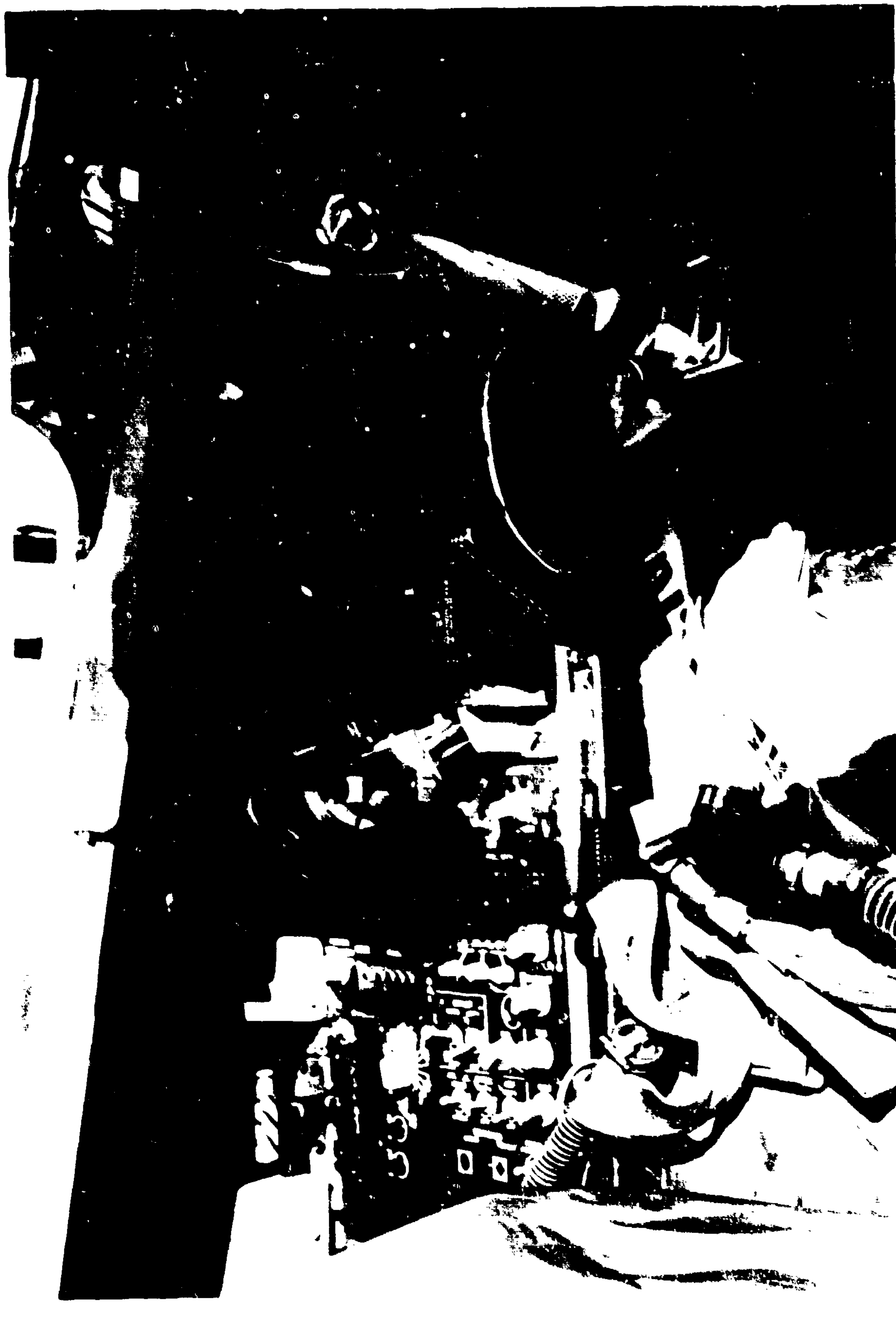

Figure 40. F-15 Cockpit - Left Side

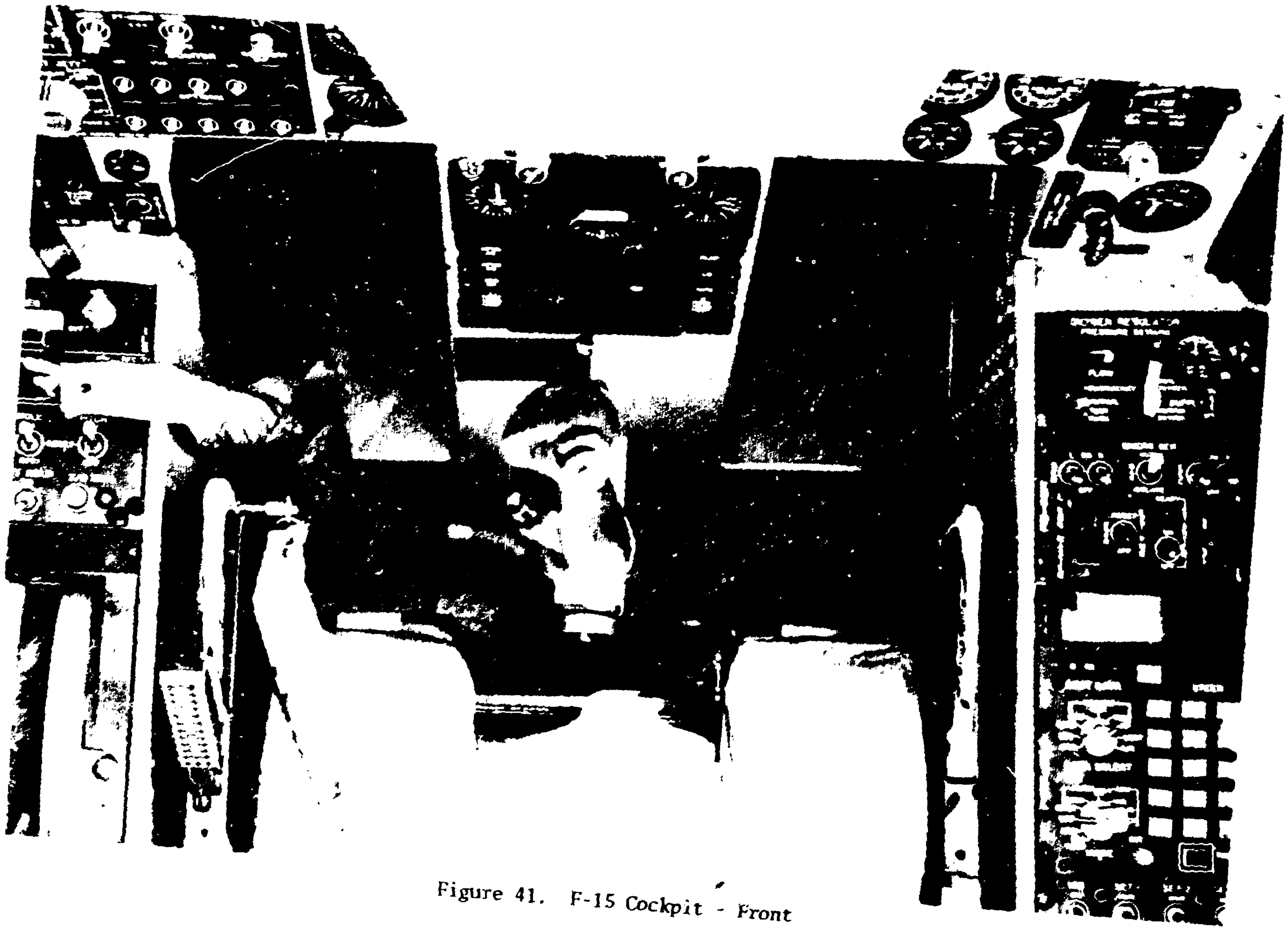

Figure 41. F-15 Cockpit - Front

Figure 42. F-15 Cockpit - Right Side

Figure 43. F-15 Cockpit - Right Rear

Figure 44. F-16 Cockpit - Left Rear

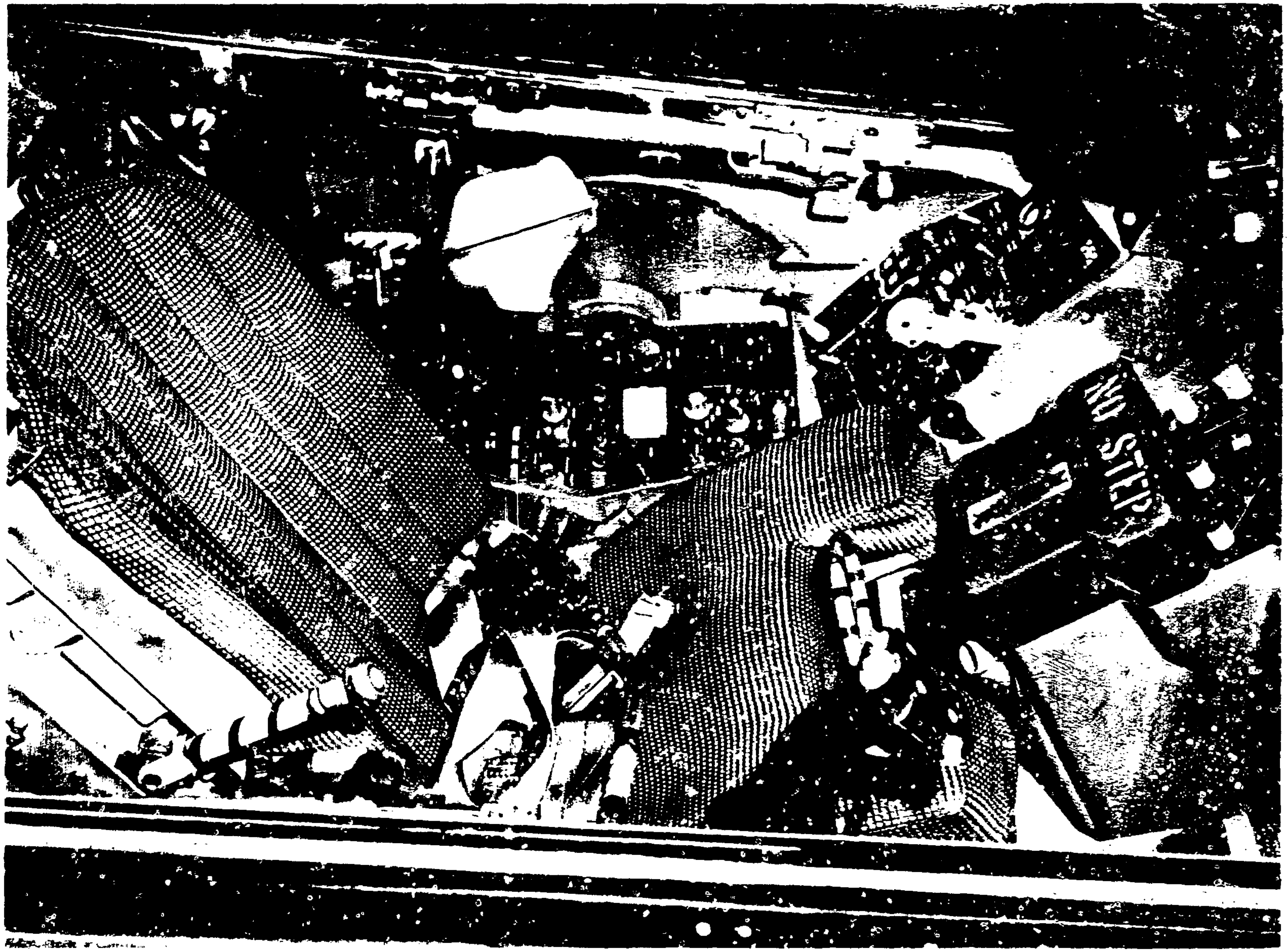

Figure 45. F-16 Cockpit - Left Side

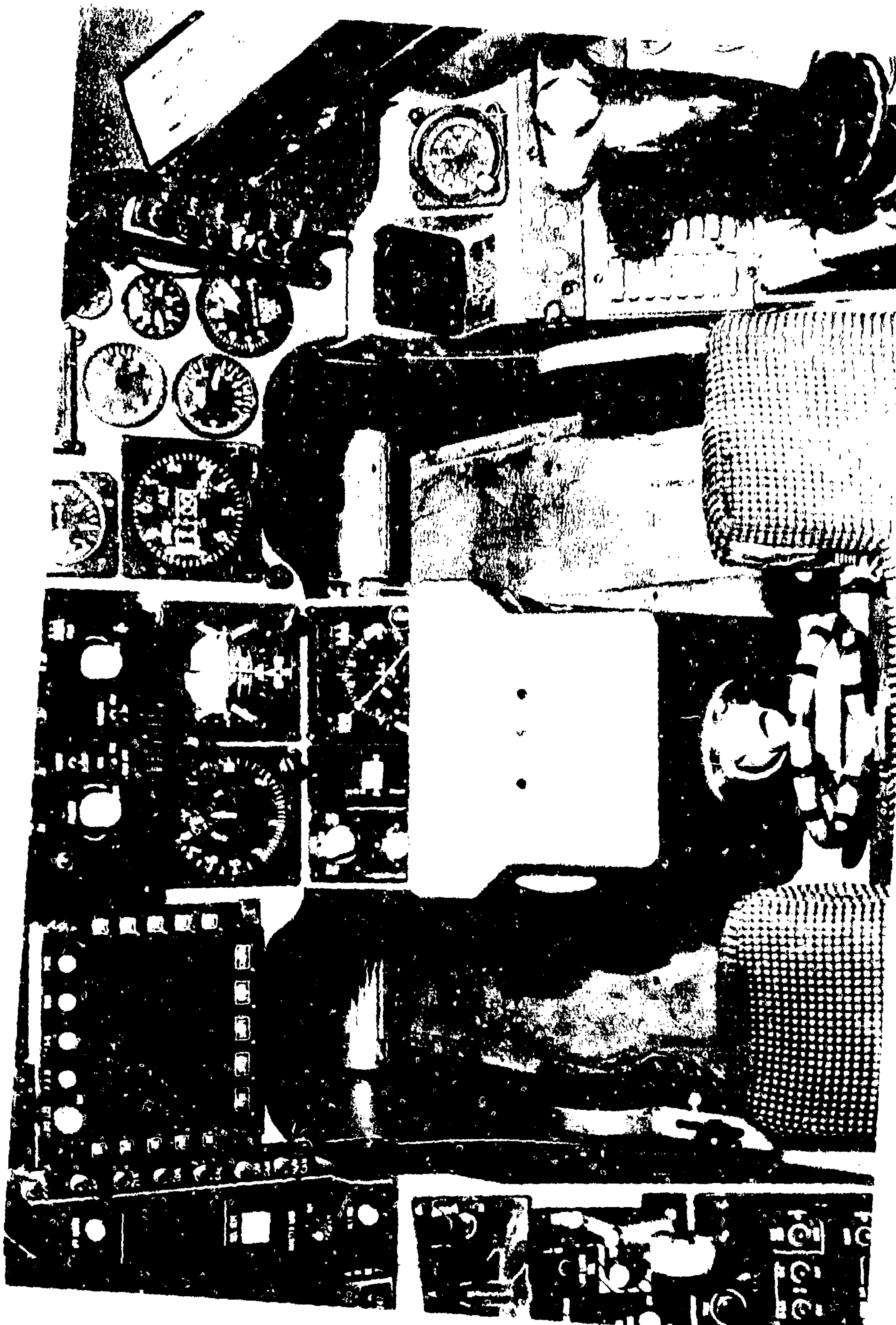

Figure 46. F-16 Cockpit - Front

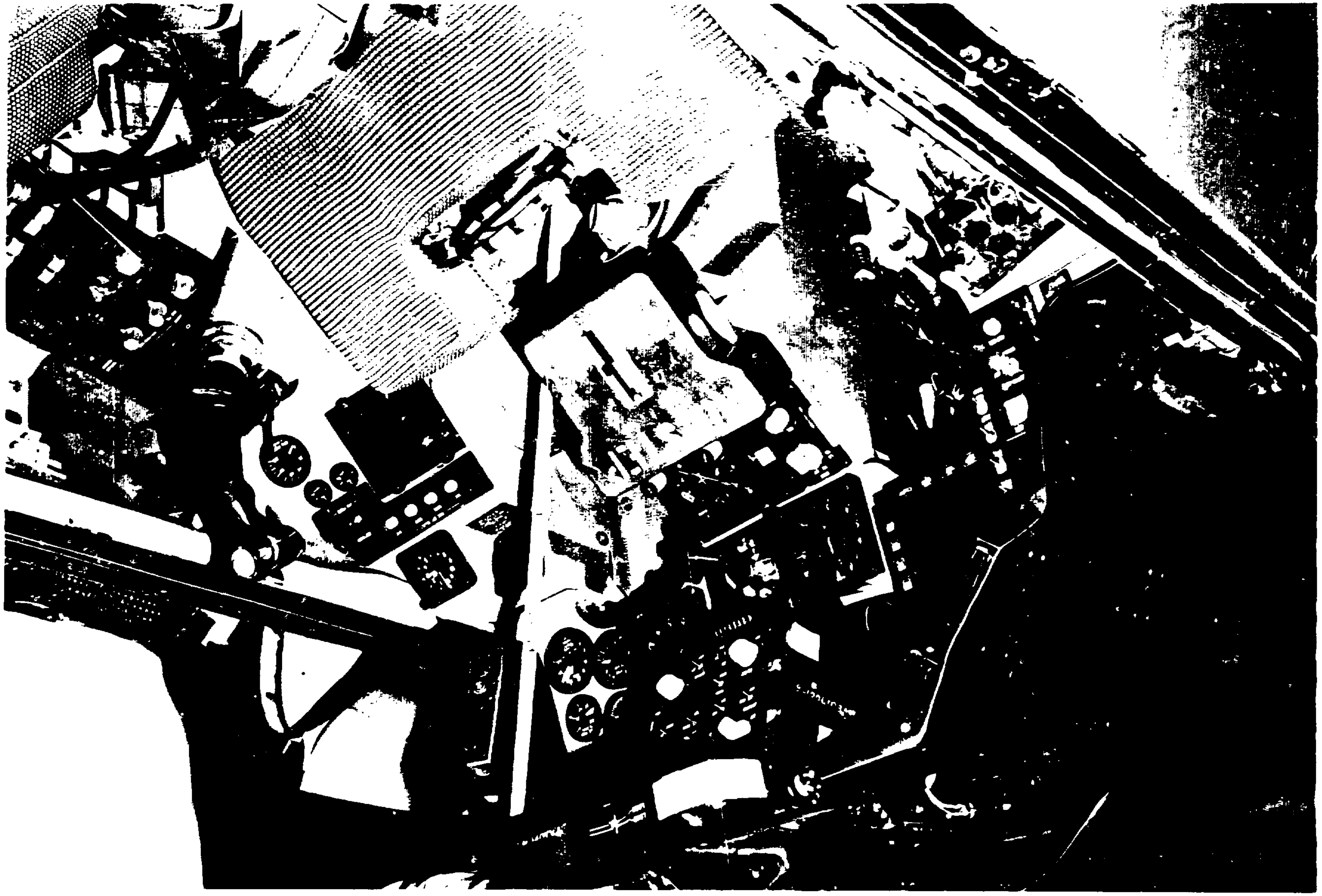

Figure 47. F-16 Cockpit - Right Side

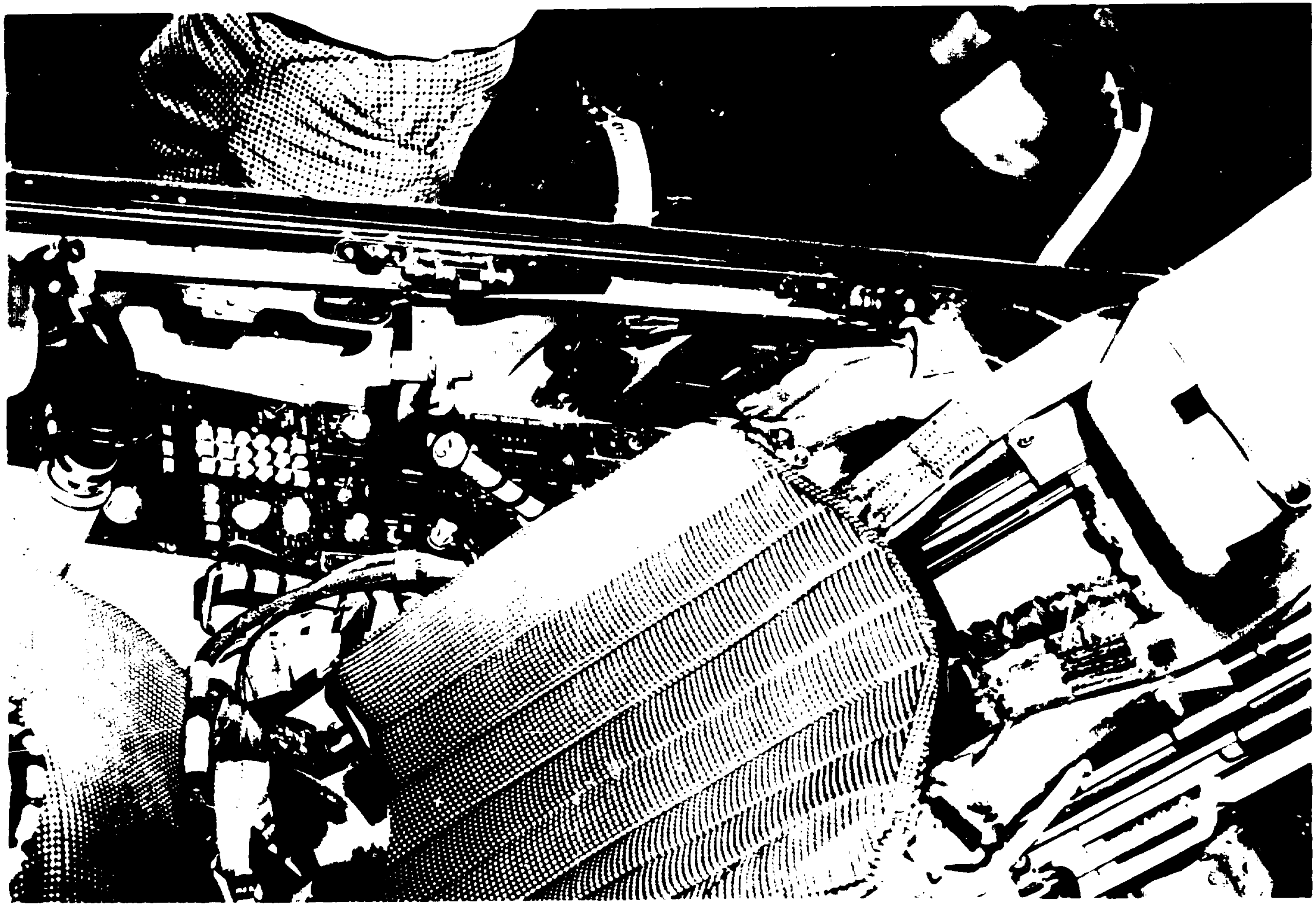

Figure 48. F-16 Cockpit - Right Rear

RESTRAINT RETRACTION SIMULATOR

This device uses a 3/4-inch diameter, 12-foot long shock cord to store energy from the stroke of a hoist. Upon release, the shock cord contracts with a force ranging from 300 to 150 pounds over a 6-foot stroke. The shock cord is stretched from one end and released from the other so that the cord need not be handled while under tension. For safety, the components of the device are overdesigned for strength, and all moving parts are enclosed within a 3/4-inch thick plywood box, except for the retracting line. The device requires only one person for its operation and takes less than 5 minutes to reset for the next firing. Figure 49 shows a side-view section of the device.

SEAT-MAN FORCE RELATION SIMULATOR

This device (Figure 50) is designed to facilitate the study of the effects of static force relationships between the seat and man on the seat-man interface. The device simulates any static force relationship at a 1 G level by enabling an occupied seat to be positioned in any attitude with respect to gravity. Safety and operational simplicity were objectives of the design. The roll and pitch rotational axes pass very near the centers of gravity of the seat-man and the whole device, respectively. Therefore, regardless of the simulator attitude, the seat-man mass never generates a gravity moment about either rotational axis. This enables the seat-man to be positioned in any attitude with only manual force and makes the whole simulator stable in any attitude. The simple operational requirements of the device encourage designer experimentation and its inherent stability provides for subject and investigator safety and comfort.

The size of the wheel, 9 feet in diameter, was chosen to accomodate the arm and leg flail spaces, provide free workspace inside the wheel for the investigator, reduce obstruction of photographic coverage of the seat-man, and provide for relative stability of the simulator when unoccupied.

The corotating movie camera mount shown in Figure 50 enables the production of films which show only the movements of the seat occupant in response to changes in the seat-man force relationship.

SEAT-MAN SEPARATION DYNAMICS SIMULATOR

This device (Figure 51) provides the capability for lifting a dummy occupied seat up off the ground with a hoist and then releasing both for free-fall over a drop of 5 to 10 feet, after which the dummy is arrested by straps attached to its parachute rig while the seat is free to continue its fall. The separation of the seat from the dummy gives a low force simulation of seat-man separation dynamics. The utility of this simulator with regard to windblast protection design lies primarily when its use is combined with slow-motion photography. Slow-motion films of a drop show the basic motions of the restraints, body, and seat during separation. These motions are complex, so this simulator can facilitate the identification of restraint release failure modes which could otherwise go unrecognized.

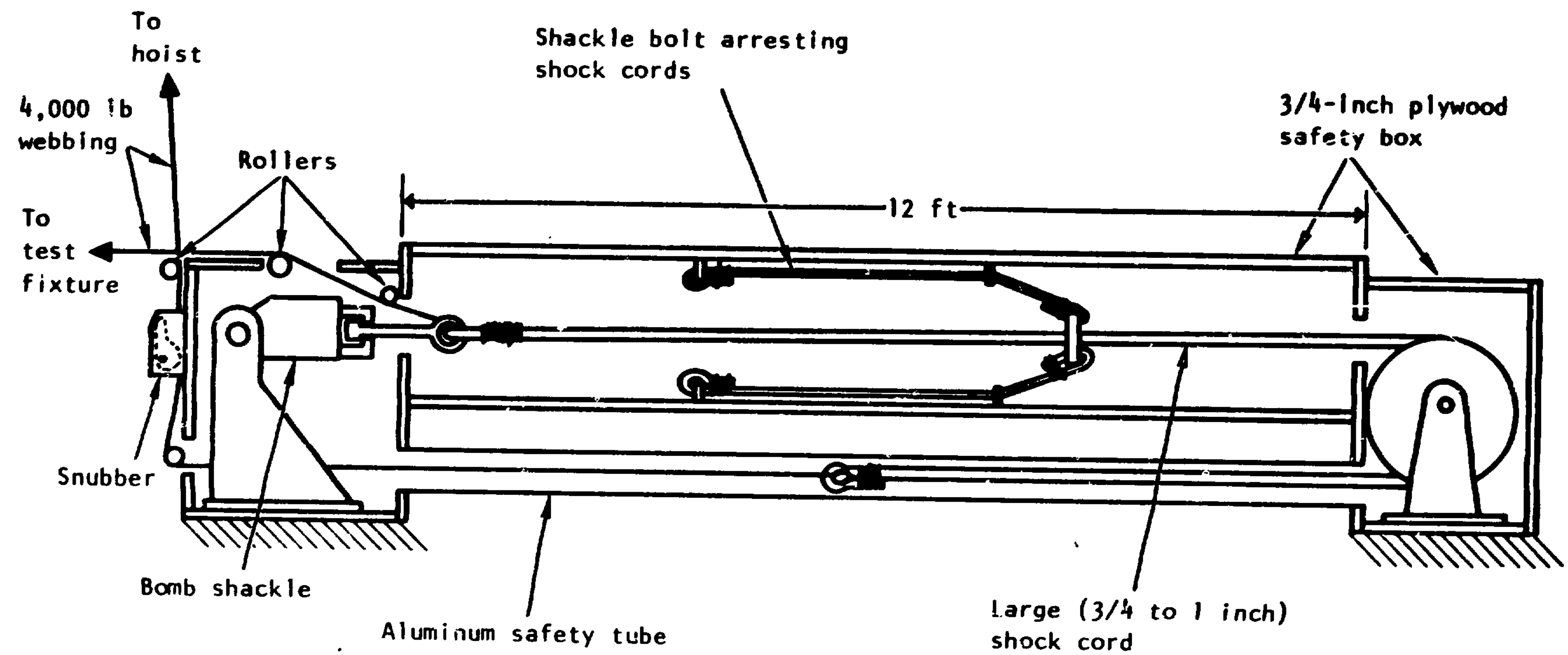

Figure 49. Restraint Retraction Simulator

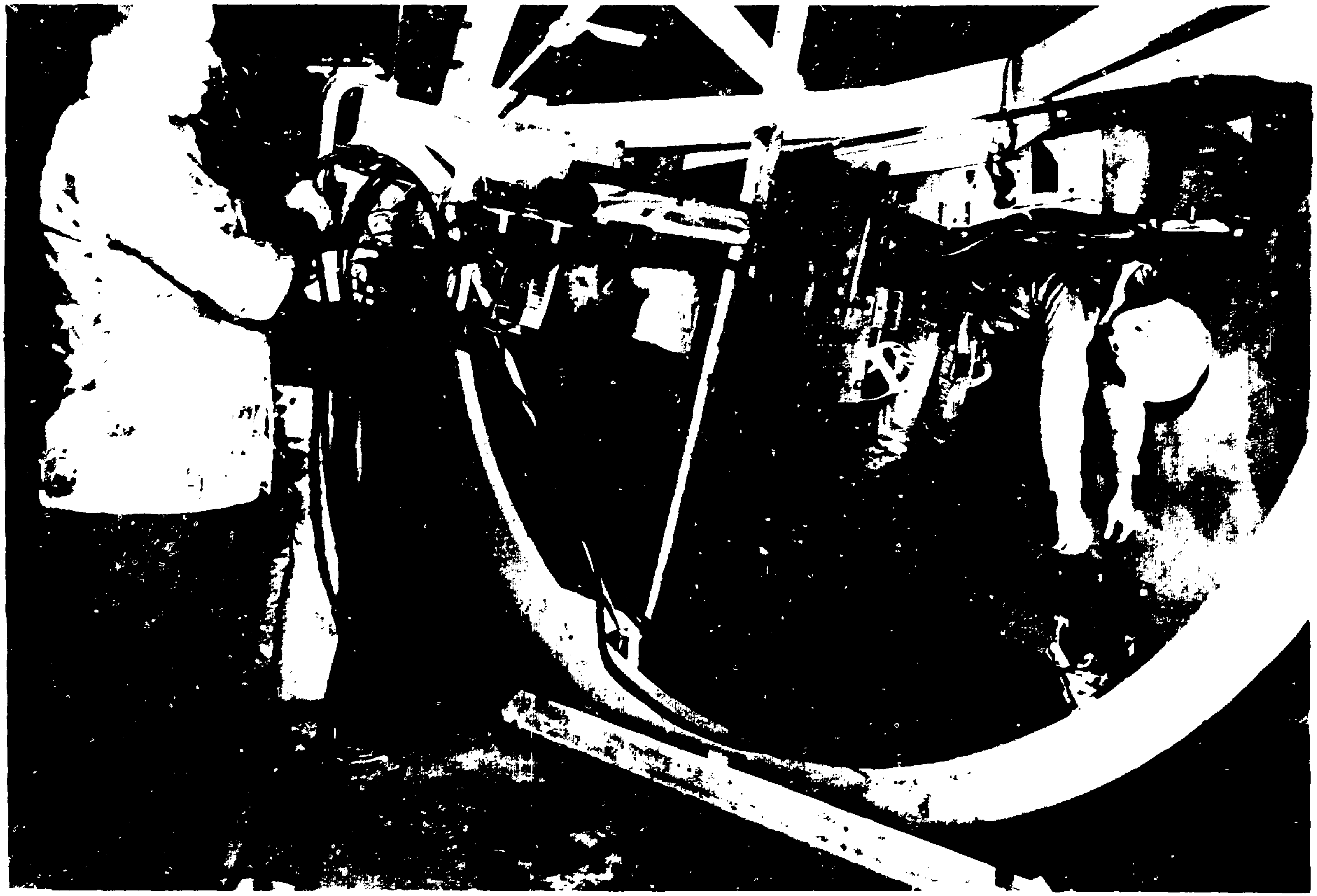

Figure 50. Seat-Man Force Relation Simulator - Showing Corotating Camera Mount

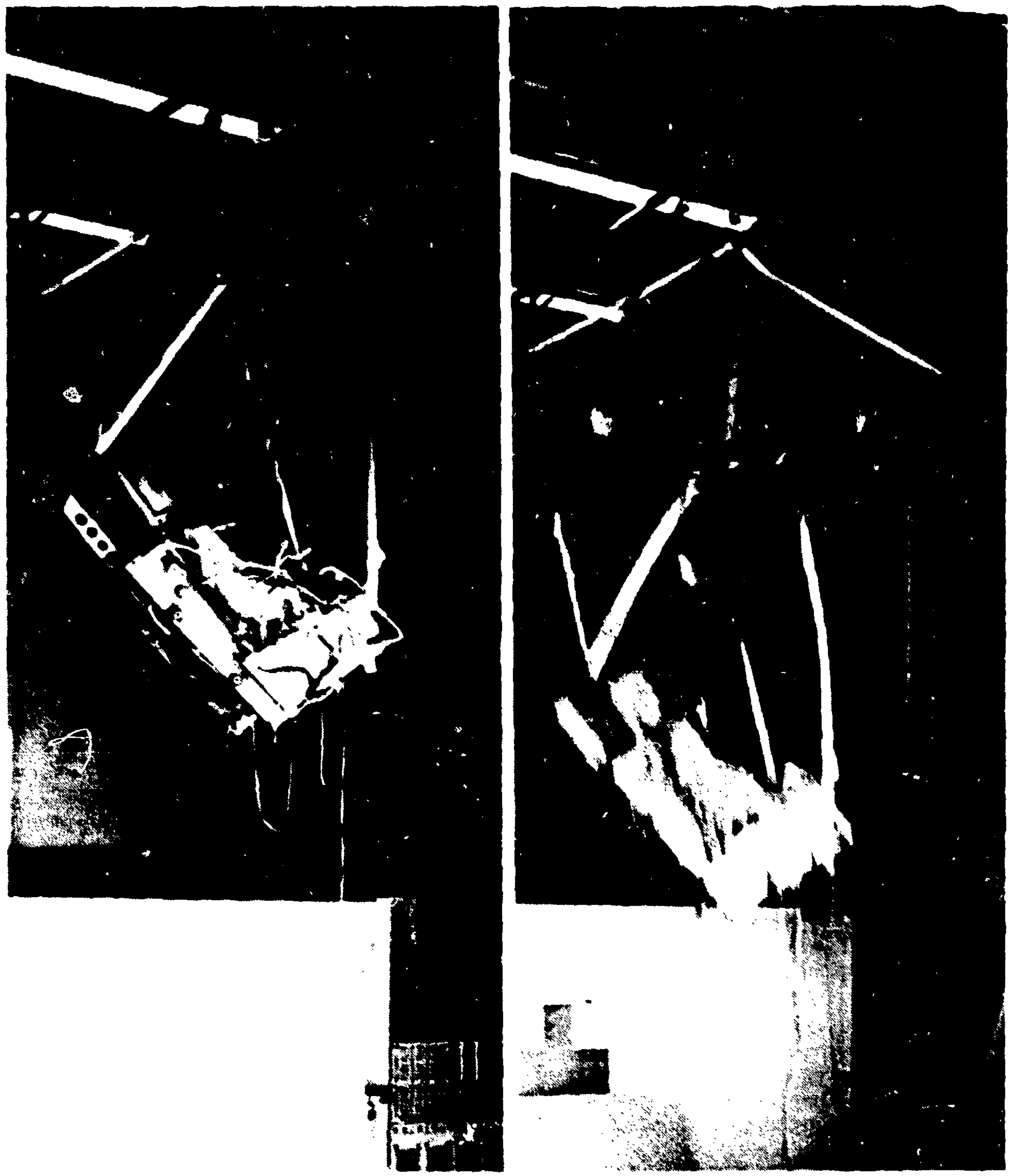

Figure 51. Seat-man separation simulator.

The development of a comprehensive, man-centered evaluation plan for windblast protection concepts was a major goal of this program. The plan developed and used is summarized in Table 3. The main headings in this table are "Fixtures", "Tests", and "Evaluations". The fixtures include the seat and prototype protection devices, as well as the four simulators. The tests are separated into those using dummies as seat occupants and those using human subjects. The left-hand grid shows the combination of fixtures employed by each test. The lists under the test subheadings, "Dummy" and "Human", are descriptions of the respective groups of tests. The 11 subheads under evaluations refer to the man-centered performance evaluations described in the following paragraphs. The right-hand grid identifies the goals of each of the tests in terms of device performance evaluations for which data must be provided.

MAN-CENTERED PERFORMANCE EVALUATION DESCRIPTIONS

Biomechanical Loading

This evaluation considers the injury vulnerability of the major limb joints and the spinal column to loads which they might have to carry, due to the protection device load-carrying characteristics, during: deployment, windblast exposure, drogue-force-induced attitude alignment with the flight path, or seat-man separation. The biomechanical loading of each joint and the spine-ribcage-pelvis should be reviewed for each protection concept; during each ejection phase; under the whole range of possible external loading conditions, including: attitude instability, linear and angular inertial response of seat and man to drogue stabilization, and unstable seat-man separations. This completeness of review is especially important in comparative evaluations where the range of external loading conditions for which protection is provided is an important performance trade.

Deployment Failure Modes

This evaluation considers the kinematics of protection-device deployment. Special attention is given to the potential of the device during deployment to interact adversely with the occupant's body, his personal equipment, or the equipment on the seat or in the cockpit. The consequences of adverse positioning of the limbs, torso, and head are considered, as are the effects of sustained aircraft acceleration loads that might exist at the time of deployment. Important potential deployment impediments to check for include the following:

1. Friction of the retracting strap over large radius curved surfaces such as a shoulder, arm, or leg.
2. A hand on a flight control or arm on an aircraft-mounted armrest.
3. Sleeve pen-pockets with pencils or pens.
4. Inflated G-suit bladders.
5. O_2 or G-suit leads.

TABLE 3. CONCEPT EVALUATION PLAN: FIXTURES AND EVALUATIONS RELATED TO TESTS

Configuration No.	Fixtures: ACES-II seat	Fixtures: NPC's (4 arm & 2 leg)	Fixtures: Retraction simul.	Fixtures: Torso retraction simulator	Fixtures: Seat-man force simulator	Fixtures: Cockpit geometry simulator	Fixtures: Seat-man separation simulator	Tests: Dummy	Tests: Human	Evaluations: 1. Biomechanical load	2. Deployment	3. Windblast	4. Seat-man separation	5. Torso positioning	6. Mobility	7. Ground egress	8. Access to re release	9. Encumberance	10. Donning/doffing	11. D-ring vs side-arm
1	●	●							No. 1 - fit/function chk	●	●	●			●	●	●	●	●	●
2	●	●	●					No. 2 - deployments over range of forces and arm positions		●	●	●			●		●			●
3	●	●	●	●				No. 3 - simulataneous deployment and torso retraction		●	●	●		●			●			●
4	●	●			●				No. 4 - seat rotation in pitch, roll, and yaw, pre and post-deployment	●		●			●			●		●
5	●	●				●			No. 5 - emergency egress and donning/doffing demonstrations							●		●	●	
6	●	●	●			●			No. 6 - deployment in cockpit simulator		●			●						●
7	●	●					●	No. 7 - seat-man separation tests					●							

Deployment in Windblast

In this evaluation, consideration is given to potential deployment failures resulting directly or indirectly from decompression and windblast effects in the cockpit or during catapult stroke. Because windblast forces acting in the cockpit may be large and the forces encountered in the aircraft flow field are greater than free-stream dynamic pressures (Newhouse et al., 1980), the protection device deployment must be insensitive to exposure to these flows or the device must be deployed before canopy release.

Seat-Man Separation

This evaluation looks for failure modes in the release of protection devices from the man at seat-man separation. Seat-man separation is studied at slow speeds using a hoist and at higher speeds using the separation simulator and slow motion cameras. Conclusions based on device performance in tests using dummies must recognize and account for the pertinent differences between dummies and humans. For example, the human seat occupant would normally be tightly gripping the ejection control at seat-man sepatation. His grip and pull could easily affect the separation in a way that might not be reproduced in a test with a dummy as the seat occupant.

Torso Repositioning Compatibility

This evaluation is based on the possibility that a seat occupant's torso may not be in the normal ejection position at the time of ejection initiation. If this were the case, the power reel may or may not retract the occupant to the normal position before catapult initiation. The protection device must be compatible with either event. Device ability to be deployed during torso retraction is studied and failure modes are noted. Device reaction to an incomplete torso retraction is also evaluated. In particular, it is determined whether eventual torso retraction would be possible after the protection device is deployed.

Mobility within the Primary Restraints

This evaluation starts with baseline information on how much mobility the seat occupant's torso has within the primary restraints after shoulder reel retraction. The mobility of the shoulder and hip joints is particularly important. The protection devices are then evaluated in regard to any potential restrictions or expansions of the baseline mobility. Normal and abnormal deployment modes should be considered. If there is any tendency for the protection device to restrict the baseline torso mobility, then the mechanism and load paths for this restriction must be identified for the purpose of determining the potential for the limbs, limbs' joints, or spinal column to sustain loads associated with torso inertial response to any of the ejection acceleration events.

Emergency Ground Egress

This evaluation assesses device conformance with the requirement for single-point restraint release capability. The protection system is also evaluated for the quality of its release with regard to trailing straps and the potential for entanglement during egress.

Access to Restraint Emergency Release Control

The emergency release control might be used after ejection initiation to manually override the aneroid controlled parachute initiator in the case of bailout over high-altitude terrain or to manually deploy the main parachute and cause seat-man separation in the event of a sequencer failure. It is unlikely the occupant could operate the control if the seat were not stabilized by a drogue chute because of seat tumbling. Therefore, this evaluation assesses the deployed device effect on baseline access to the release control when the seat and occupant are facing toward the ground as though descending on the drogue parachute.

Crew Encumbrance

In regard to windblast protection devices, encumbrance could be caused by:

1. Interference with internal or external vision.
2. Interference with either reach or body mobility.
3. Discomfort due to weight, heat, or annoying pressures on the body or limbs.
4. Rigging instability requiring readjustment, repositioning, or unsnagging in flight.
5. Mistrust due to perceived complexity or messy appearance.

This evaluation begins with a baseline study of vision, mobility, access, and comfort with the ejection seat (in this case the ACES-II) and personal equipment items used by fighter crews. The impact of the device design on these factors is then studied and reported.

Ingress/Donning, Egress/Doffing

Device impact on the baseline ingress/donning and egress/doffing procedures is evaluated with regard to extra time required and difficulty added. Also the potential for improper donning is studied and reported.

D-Ring, Side-Arm Initiation Mode Compatability

This evaluation considers device suitability for use with side-arm and/or center-pull-type ejection initiation controls. The impact on device deployment due to the difference between the arm positions associated with the two types of controls is studied. Also the nature of the restraint forces, if any, applied to the arms while the hands grasp the controls is determined. In center-pull seats, the hands are pulled between the legs during seat-man sepatation, while in side-arm-type seats the arms are pulled over the sides of the hips. The potential impact of these arm motions on restraint release is evaluated.

DESIGN EVALUATIONS

The windblast protection device tests were conducted as indicated in Table 3 for each of the six windblast protection system designs. Where appropriate, human subjects of critical anthropometric size were employed. The exploratory orientation of the testing (i.e. to discover and understand as many potential failure modes as possible) helped in the identification of subtle problems which otherwise could easily have gone unnoticed. As the testing progressed, a better understanding of the special aspects of the design problem developed and contributed to the discovery of many design improvements. The simultaneous testing, evaluation, and design modification of several alternative design approaches seemed to stimulate the discovery of useful hybrid design ideas. This effect was strong and should be exploited during the next stage of windblast protection design development when several more alternative design concepts should be available (e.g., magnetic capture and release, and deployment assisting inflatables).

Real-time and slow motion films were made of most of the tests. An edited film was submitted with this report. The design evaluation results are summarized in the following paragraphs.

CONCEPT 1 - ARM STRAPS

Biomechanical Loading

The "arm straps" device provides the arms with the best protection against windblast effects. The upper strap, which runs around the torso and over the lower area of both upper arms, protects the shoulder and supports the elbow against forward forearm dislocation. The wrist collar pulls the wrist toward the belt buckle, preventing forearm hyperextension and backward elbow dislocation (see Figure 17).

Deployment

The deployment performance is good, because of the positive capture and positioning of the limbs in command ejections. However, there are potential deployment failure modes, including the upper arm strap snagging on the shoulder or objects in the sleeve pockets, and the wrist collar strap snagging on a harness-mounted regulator. However, correct donning and small design changes could make the risk small (see Figure 16).

Windblast

Sensitivity to windblast should be low because the straps are under tension during deployment and have low presented areas. Because the wrist collar pulls near the end of the arm, the arm straps have the best mechanical advantage for positioning the arms, even in windblast.

Seat-Man Separation

Seat-man separation is accomplished by cutting all four retracting straps. The upper arm straps must be pulled through the belt rings before separation is complete. The wrist collars stay with the man, but only short lengths (less than 12 inches) of restracting cord are attached to them, making entanglement unlikely.

Torso Positioning

Abnormal torso position would not add any new deployment failure modes. Deployment of the upper arm strap off the shoulder is more difficult, and snagging on sleeve pocket contents is more likely. However, if deployment is successful, the arm straps provide good windblast protection with the torso in any position and, in particular, the quality of protection is insensitive to torso movement after deployment.

Mobility

The baseline mobility of the torso in the primary restraints may be indirectly reduced by a small amount by the pressure created over the upper portion of the thighs by the tension in the wrist collar straps. Otherwise, the arm straps carry no torso loads.

Ground Emergency Egress

Ground emergency egress requires cutting the four retracting straps, resulting in 3- to 4-foot lengths of cord attached to the wrist collars and upper arm restraint straps. These lengths of cord must be either shed off the body or trail along from the wrist collars and would appear to present a potential for entanglements during egress. However, several emergency egress demonstrations with the arm straps were conducted without any problems. (See Figures 52 and 53.)

Access to Restraint Emergency Release

Access to the restraint emergency release handle depends on the amount of strap left between the wrist collar and the belt ring. When only 2 to 3 inches remain, demonstrations showed that handle access and operation were difficult.

Encumbrance

The appearance of the arm strap system is messy. The retracting straps cannot be concealed in a sheath because of the danger of jamming during retraction. The need to don the wrist collars also may be encumbering to some. The system does not reduce internal or external visibility. Because of the geometry of the wrist-collar cord (i.e., always tensioned between the wrist and shoulder), the visual projections of the cords, as seen by the seat occupant, always fall on the occupant's arms. Under 1 G conditions, the operational appearance of the cords was judged to be good. Under vibrating conditions, cord movement could be distracting. An important advantage over existing designs using similar protection strategies is the absence of a worn garment and its associated sizing and thermal comfort problems (see Figure 14).

Donning/Doffing

To don one side, the two retracting straps are lifted and the arm and shoulder are slipped underneath; then, the wrist collar is grasped and pulled forward. Any twists around the retracting straps are undone, and the collar is donned around the wrist and cinched down. The collar is designed so that once in hand, it can be donned and cinched in under 3 seconds. The elasticity of the built-in 1/8-inch-shock cords controls retracting cord slack after donning with a nonannoying shoulder-ward pressure on the wrist. (See Figure 13).

Figure 52. Arm Straps - Emergency Egress Evaluation, Restraint Release

Figure 53. Arm Straps - Emergency Egress Evaluation, Abandoning Cockpit

D-Ring/Side-Arm Compatibility

The arm straps system works equally well with either D-ring or side-arm ejection initiation control handles.

CONCEPT 2 - DEPLOYABLE SLEEVE

Biomechanical Loading

The primary component of the deployable sleeve is a cloth cylinder. A strap loop passes through the inside of the sleeve, and one-half of the loop is sewn to the sleeve along its length. At both ends of the sleeve, the strap passes through metal rings. This ring, via the strap loop, pulls the sleeve down the arm and tensions both the strap loop and sleeve between itself and the shoulder ring. Evaluation of the biomechanical loading characteristics of this device found that the lower arm was supported over a broad area but that no support was given to the upper arm. Therefore, aftward forces on the upper arm caused the elbow to flex and pull the forearm through the sleeve until either the elbow slipped out of the shoulder opening, releasing the arm, or the upper arm wedged between: tensioned cloth of the sleeve, which focused at the bottom of the elbow; and the shoulder girdle limit of upward motion. These biomechanical loading characteristics were judged unacceptable.

The deployable sleeve design was dropped from further consideration because resolution of the biomechanical loading deficiency was not thought possible within the constraints of a deploying sleeve strategy. However, evaluations of Concept 2 led directly to the design solutions embodied in Concept 5, the arm length sleeve.

CONCEPT 3 - LEG STRAPS

Biomechanical Loading

The leg strap device provides good protection from leg flail and knee injuries. The windblast loads on the upper leg are carried through the femur to the upper leg strap, which cinches down just above the knee. The knee ligaments are further protected by the lower-leg-support-strap, which holds the lower legs off of the seat-bucket forward panel. This allows the lower legs to move up past the front edge of the seat pan until the upper leg restraint strap becomes active. The lower leg restraint strap encircles the lower leg, but does not bind it. This prevents flail, but avoids adding torques to the lower leg and knee joint and allows upward movement of the lower leg to relieve strain in the knee ligaments.

Deployment

The leg strap device exhibited a serious deployment failure mode during testing. This involved snagging of the upper-leg-strap wand in an opening of the anti-G garment, near the hip. No solution for this problem was identified at the time of testing and further consideration of the concept was dropped. Near the end of the program, solutions which solved the deployment problem were discovered. With the snagging problem fixed, a second, but less likely, deployment problem surfaced. This was a tendency for the upper leg strap to whip forward in front of the knee, rather than just above it. This failure is considered resovable by adjusting the attachment of the retracting strap to the wand.

Deployment of the lower leg restraint strap from its stored position around the leg well appeared to be attainable with a 2-to-1 takeup rate during catapult stroke. Tests were conducted wherein the seat with a subject in it was lifted out of the cockpit-geometry fixture with a hoist, to study the timing of retraction process. It was found that the lower leg strap could be pulled from the top of the leg well toward the seat before the ankle reached that height. Therefore, capture of the lower leg could be assured.

Seat-Man Separation

One end of both the upper and lower leg restraint straps is released at seat-man separation. Release is complete when these straps have pulled over the tops of the legs. Since the straps are free at release, this is judged a good design.

Encumbrance

Only the upper leg strap is donned. It is routed over the upper leg near the hip so that it is out of the way and does not interfere with leg movements.

After the leg strap detailed drawing in Table 2 was completed a new configuration was discovered which eliminated the need for donning or doffing the upper leg strap. When deployed the new strap configuration runs through a metal ring at the lap belt buckle then over the thigh to the front corner of the seat pan. When stowed, the strap, instead of running over the thigh, runs back down the lap belt through a ring attached to a deployment assisting spring wand and then forward to the front corner of the seat pan. Thus donning and doffing are accomplished simultaneously with belt buckle closing and opening.

CONCEPT 4 - G-SUIT MODIFICATION

Biomechanical Loading

This leg restraint concept gives excellent leg protection. Restraint loads are spread over a large area, so pressures are low. Since the G-suit is pulled from beneath the upper leg, it will pick up much of the windblast load directly, thereby partially shielding the leg from loads it would otherwise have to sustain. The G-suit design was changed toward the end of the program to include a lower-leg-support-strap like that of the leg-strap design. This permitted a second change, from two independent retracting straps for the upper and lower leg, to a single strap per leg. This improved donning performance without sacrificing protection (see Figures 23 and 24).

Deployment

Deployment is very reliable and safe and can be accomplished satisfactorily using seat motion. The high level of reliability should encourage use and mitigate the inconvenience of the four required connections.

Windblast

Since the retracting straps are beneath the legs and deployment is complete after less than 12 inches of test motion, the deployment of the G-suit modification concept is insensitive to windblast effects. The capacity of the G-suit to carry windblast loads on the leg is probably limited by the inseam zipper's

load capacity which is specified (minimum) about 250 lb per 6 inch length. The restraint attachment modification designed to spread loads evenly over about 8 inches of zipper for at least a 300 lb capacity for the zipper and an estimated 600 lb capacity for vertical force on the leg. The highest force area for vertical leg forces reported by Payne et al. (1975) was about 0.35 ft^2 which is equivalent to about 470 lb per leg at 600 KEAS.

Seat-Man Separation

After one end of the retraction strap is released, that end must be pulled through the upper and then through the lower leg snap hook eyes before release is complete. The design of the release fitting and the snap hooks must be carefully checked to verify that no hangups are possible. Also, the donning procedure must be clearly indicated in order to guard against twists in the straps which would cause jamming.

Mobility

The G-suit restraint system design avoids transfer of body inertia loads to the knee ligaments by providing inherent slack to accommodate movement of the torso in the primary restraints.

Ground Egress

No release or entanglement problems were observed in connection with emergency ground egress.

Encumbrance

The G-suit restraint straps are not normally visible during flight, because they are hidden beneath the legs. There is no restriction of mobility or sensation of restraint. The system is simple in design and operation and is easily understood. The required modification to the G-suit can be accomplished by any military parachute loft after the suit has been fitted to the pilot. If modification is made before the G-suit is fitted, adjustment of the leg lacings will be more difficult. The modification is neat in appearance.

Donning/Doffing

Donning and doffing involve the attachment and release of four snap hooks, two of which slide freely on both the left and right retracting straps. Donning takes about 5 seconds per leg; doffing, about 3 seconds per leg. Donning is easiest when the hook openings are held facing away and the hooks are inserted through the G-suit rings before snapping. The design of the retracting strap loops helps avoid misdonning by having one end of the loop placed above the other. With one hand, it is easy to locate the correct loop and its upper and lower sides near the seat, even if the subject is blindfolded. With a finger keeping the two sides separate, the loop is pulled up between the legs. This automatically removes any twists in the loop and causes the snap hooks to be drawn into the hand in the correct orientation, ready for insertion in the G-suit rings. With this procedure, donning and doffing performance is considered good, despite the four required connections. The snap hooks used for evaluation are those shown in Figure 19. The evaluated hooks operated well, but were not strong enough. The specified hooks have an appropriate load rating, but have not been evaluated for operation. A new hook design may be required.

D-ring/Side-Arm Compatibility

The G-suit leg restraint performs equally well with either D-ring or side arm ejection initiation handles.

CONCEPT 5 - ARM-LENGTH SLEEVE

The arm-length sleeve is designed to be a permanent part of the ejection seat's restraint system rather than a new article of personal protective equipment. The advantages are no connections or adjustments added to the ingress procedure and good logistics, maintenance and life cycle cost performance. The universal fit approach reduces complexity and weight and supports design-to-cost goals, while presenting the potential for a significant improvement in windblast protection. The concept also has potential for successful acceptance by flight crews, because of its simple design, light weight, low detectibility in use, ease of donning and doffing, highly reliable deployment, and its status as a permanent component of the seat restraint system.

Potential disadvantages include objections from lower percentile flight personnel regarding excessive looseness, less-than-perfect restraint of limb movements relative to the torso, integration problems with the shoulder strap takeup system, and emergency egress interference problems.

The sleeve is a bent tube of nylon fabric specially shaped to support the upper and lower arms against windblast loads while avoiding generation of loads in the shoulder and elbow joints (Figure 54). The shoulder opening is held open by a piece of stiff nylon tubing and this provides for good donning and doffing performance. A loop of webbing is sewn to the inside perimeter of the shoulder opening and its ends are sewn to a metal ring which hangs on the shoulder strap connection to the parachute riser. A second continous loop of strap is routed through both openings of the sleeve and over its outer surface. The lower loop is permanently fixed to the sleeve only near the wrist opening on the inside. The rest of this loop is sewn to the sleeve with rip-out stitching. This loop is also threaded through a steel deployment ring normally located beneath the armpit. A lanyard attached to this ring is pulled toward the forward edge of the seat pan during deployment. As the deployment ring moves in response to the lanyard's pull force, it rips out the stitching on the lower strap loop. Eventually the moving deployment ring tensions the lower loop against the sleeve and, thereby, provides support against windblast forces. The upper strap loop supports the lower loop and prevents the sleeve from sliding down the arm. A connecting strap creates a tension load path between the top leg of the lower loop and back leg of the upper loop (refer to Figure 9). This link prevents the lower sleeve from moving backward under load by preventing rotation of the lower strap loop through the deployment ring.

For restraint release, the retracting cord which pulls the deployment ring is cut and the large shoulder ring slips off the released shoulder restraint pulley. For emergency ground egress, the retracting cord is released from the deployment ring by tension in a sheath over the retracting cord created by the egress motions of the occupant.

Figure 54. Sleeves - Showing Large Load Distribution Area

Biomechanical Loading

Because the sleeve is shaped to receive a flexed arm and is suspended on a taut strap, the restraint loads are spread evenly and over a large area so that maximum restraint pressures are very low. (See Figure 54.) The elbow is protected, because the sleeve keeps the arm in a flexed posture and supports the upper arm near the elbow and the lower arm near the wrist. The looseness of the sleeve makes it inherently conforming to the shape of the arm and should make it tolerant of high dynamic loadings despite its lightweight construction. The retracting strap stops at a predetermined position which prevents excessive pulling of the sleeve against the arm. When the shoulder reel has fully retracted, the sleeve gives immediate support to the upper arm against upward and backward acting forces. This will help the occupant retain his grip on the initiator. Lower arm restraint is provided only after the grip is lost. Because the anti-rotation strap is connected to the windblast load bearing lower loop, some of those loads might be passed under the arm and around the back to the shoulder harness support ring. The approximate 45 degree load path angle would result in about 85 lb of downward force on the ring for each 100 lb tension in the antirotation strap. Assuming that half of the downward load would be carried by the inertia reel strap and half by the parachute riser over the shoulder, there could be 85 lb total downward force on the shoulders for each 100 lb tension in the antirotation straps. More data about the loading of the antirotation strap during windblast exposure are needed before the significance of these shoulder loads can be ascertained.

During deployment, as the deployment ring is pulled down the outer side of the strap loop, light thread stitches which hold the strap to the outside of the sleeve are ripped out. This puts only a light load on the arm, as the ripout can be performed with manual force.

Deployment

Because the arm is precaptured in the sleeve, deployment is greatly simplified and therefore is highly reliable. If an off-seat, low-pressure oxygen line is required, it should be routed under the retracting strap, as should the G-suit supply hose, since both of these present potential deployment hangups. The sleeves will reposition out-of-position arms and, therefore, provide good protection, even in command ejection situations. If built in accordance with the drawing, about 18 inches of seat travel (i.e., 24 inches above full-down) at a 3-to-1 retraction ratio would be required to complete deployment. This is not good, in terms of both the seat travel and retraction ratio. If the retraction strap were routed more directly to the deployment ring, this number could be reduced to 15 inches at a 2-to-1 ratio, or 10 inches at 3-to-1. If routed from under the shoulder to between the legs (requires connection at donning), the required seat motion would be 10 inches at 2-to-1 takeup.

Windblast

The deployment will be insensitive to windblast loading. The response of the sleeve itself to windblast loads is not known. There is a possibility of severe flutter and the associated "flag drag", in the sleeve material. The arm and sleeve as a unit may also flutter, but this should not be a problem, because of the short exposure to the flutter exciting conditions and relatively large inertial mass of the arm versus the sleeve.

Seat-Man Separation

Given a successful cutting of the retraction cord, release of the sleeve involves an estimated 25-pound force on the retraction-cord-sheath to release the sheath pin and the deployment ring. The release of the shoulder ring off the should-retraction pulley was tested, and no problems were observed after release of seat-man separation, however, release was sensitive to ring diameter. The sleeve will probably collapse down to the wrist. If it is not removed before landing, entanglement is possible.

Torso Positioning

The retracting strap stroke is stopped at a point which precludes its cinching against an incompletely retracted shoulder harness. With the torso leaning full forward after deployment, the strap loop through the sleeve is slack, and no immediate arm support is provided. Also, the distance between the connector strap at the shoulder opening and the deployment ring below the initiator is much shorter so that the forearm is able to move three-fourths back before it is arrested by the sleeve. Nevertheless, the biomechanical loading is acceptable. Therefore, the sleeve still provides gross flail protection in the torso-forward case, but the quality is less than for the normal torso position. Postdeployment torso repositioning may be impeded by the sleeve because, if the sleeve has been blown back, the strap loop must be pulled through the deployment ring as the torso moves back toward the backrest. For that to happen, the sleeve and arm must be pulled forward toward the ring, against the windblast.

Mobility

The sleeve indirectly reduces mobility in the primary restraints by pulling down on the parachute risers behind the shoulders during initial windblast exposure. However, this would not cause the arm bones or joints to carry any torso-generated inertia loads.

Ground Egress

Human subject ground egress evaluations showed that release of the retracting lanyard from the deployment ring was a problem area. For the evaluations, the force required to pull the release pin was in the area of 20 to 30 pounds. At this force level, inadvertent release is unlikely. However, as the seat occupant stood up during egress, the sleeves were pulled down the arms by the retracting cords before the pin pull force was attained. With the sleeves at the wrists, the pin force was dangerous in that it could hold an arm back as a subject attempted the emergency egress procedure. Several design modifications involving linking the left and right sleeves together to hold them on the shoulders were tried, but these caused unacceptable difficulties in donning and doffing. If the seat occupant lifts his arms as he stands, release is clear and unnoticable. However, it is wrong to rely on procedural remedies for design problems, especially in emergency situations. Therefore, the release force should be lowered, with the possible trade-off being more inadvertent releases.

The release of the shoulder ring was also a problem area. The weakness of the inertia reel spring in the ACES-II seat results in slow of stalled retracting of the reel strap after a forward-aft movement by the seat occupant. This in turn results in slack in the reel strap, allowing the pulley to be pulled through the sleeve shoulder ring during a reach. The problem can be cleared by leaning

forward and back with the shoulders held back. However, if emergency egress begins with a pulley pulled through one of the sleeve rings, the reel strap can jam against the pulley and ring, thereby preventing reel strap release. A stronger reel spring or light tack cord to hold the ring to the riser are possible fixes.

Access to Restraint Emergency Release

The deployed sleeve does not permit satisfactory access to the restraint release handle. A possible fix would be to add a second restraint release control on the side of the seat bucket accessible to the sleeve-restrained hand.

Encumbrance

When donned, the sleeve is neat in appearance and accommodates the complete range of cockpit mobility without restrictions. There are no annoying pressures or movements of material. The sleeve enlarges the diameter of the jacketed arm slightly, therefore, reducing internal vision. The shape of the sleeve fits that of the arms when the hands are on the flight controls. This enhances fit comfort. Thermal comfort could be reduced, because the sleeve adds to the insulative properties of the flight jacket. This could be checked in flight tests. The problem with the configuration instability of the aforementioned reel strap, pulley, and sleeve shoulder ring would probably be considered an encumbrance by the seat occupant. The deployment and release mechanisms of the sleeve are easily understood and accessible for visual and manual inspection. These features should engender confidence and mitigate the inconvenience of donning and doffing the sleeves, thereby contributing to their psychological acceptibility.

Donning and Doffing

The parachute risers are normally laid over their respective corners of the seat back pad in preparation for ingress. The sleeves, which hang from the pulley attachment to the riser, naturally flip over with the arm-hole facing forward when the risers are so positioned. After ingress, the occupant leans forward, twists, and reaches back to place his hand in the arm-hole of the sleeve. As the occupant leans back, the arm moves naturally down through the sleeve. The occupant then reaches for the parachute riser as he normally does and, with its connection to the harness, donning is complete for one side. The time added to the ingress procedure is on the order of 4 to 8 seconds per sleeve after some practice. Doffing is also easy where the proper procedure is used: after releasing and laying the riser over the shoulder, the occupant leans forward, grasps the end of the sleeve, and holds it as he pulls the arm out of the sleeve by twisting the shoulder back. This adds 3 to 6 seconds per sleeve to the egress procedure.

During the development of the arm-length sleeve concept, consideration was given to the feasibility of attaching the arm-hole of the sleeve directly to the integrated harness. A mockup of this configuration revealed some advantages and disadvantages. Emergency egress was improved, because the sleeves could no longer be pulled down the arms when the seat occupant stood up. Donning improved, because the sleeves were donned prior to ingress. Encumbrance would improve, because sleeve size could be matched to the size of the wearer and the potential interference with normal shoulder strap takeup would be removed. Biomechanical loading would improve, because the retracting strap could be routed between the legs providing a better load reaction direction. D-ring versus side-arm compati-

bility was better, again because of the direction of the retraction force between the legs. Post deployment mobility in the primary restraints could improve, because no downward loads would be placed in the parachute risers.

On the disadvantage side, donning would require two new attachments (release at egress could be automatic). The maintenance, logistics and procurement costs would be several times larger than the universal fit sleeve design. The bio-mechanical loading of the spine could be worse because vertical loads on the upper torso resulting from arm restraint retraction would not be partially dumped into the shoulder retraction straps.

While the integrated harness and sleeves concept was rejected, it is important to note that this rejection was based on an early sleeve design. The early sleeve designs were straight and were suspended from a tension load path from the headrest area to the forward edge of the seat pan. The later sleeve designs hold the arm in a bent position so that restraint forces can be applied directly to the back of the upper arm without the necessity for a tension load path to the headrest. There are potential advantages in an integrated harness/sleeve concept employing the later sleeve design approaches which were not evaluated by prototyping and test-fixture studies. These potential advantages should be evaluated.

D-Ring/Side-Arm Compatibility

While the grip on the ejection initiator handle is intact, the sleeve will provide better support to the occupant of a side-arm ejection control equipped seat than to that of a D-ring-equipped seat. After the grip is lost, however, protection is equal. Deployment works equally well for both types, as does release.

CONCEPT 6 - NET/EPAULET

Biomechanical Loading

After deployment, the net/epaulet system provides some support to the upper and lower arms while the hands remain on the initiators. The retracting strap and lower arm support strap give immediate lateral support to the lower arm. This could help the occupant maintain his grip on the initiator handle under windblast loads. The net also provides good lateral restraint to the upper and lower arms near the elbow, primarily through the second and third radial strands of the net. Restraint against aftward acting forces is not present while the grip is maintained. If the grip is lost, the arm can move back 1 to 5 inches before the net is contacted. When the arm is back against the net, the first and second radial strands restrain the upper arm, while the lower arm is supported by the lower arm support strap near the wrist. The placement of restraint forces on the upper and lower arms is good for elbow and shoulder protection. The elbow can poke through a hole in the back of the net between the second and third radial strands, and thereby be exposed to the thin edge of the storage channel opening. This is a potential injury source.

Deployment

The net/epaulet concept has had a history, on the B-1 test program, of deployment problems. The most common failure mode involved insufficient lateral extension of the net, and resulted in the retracting strap slipping between the elbow and the torso and hanging on the upper arm.

This was remedied by (1) replacing the 0.094-inch spring-wand in the B-1 net with a stiffer 0.125-inch spring-wand, and (2) rigging a lanyard between the top of the spring-wand and aircraft structure. The result is that seat motion forces the spring, via the lanyard, to deploy the net and retracting strap laterally more than 12 inches beyond the side of the seat. This eliminated the inside-the-elbow failure mode. A second historical failure mode was due to epaulet design problems. Originally, the epaulet, which hangs from the parachute riser on top of the shoulder, was designed to hang over the shoulder to preclude retracting strap hangup on the top of the shoulder. However, this design was found to be annoying, in that it caused the occupant nearly unconsciously to pull the retracting strap up to the top of his shoulder. To correct this, the epaulet was shortened. That, in turn, created a new problem wherein the epaulet would randomly pop its velcro closure open, if not tacked closed with thread; if tacked, the epaulet could jam up and not release the retracting strap from the shoulder, even if the tacking used were light. The design was changed to its final configuration in which the retracting strap is held between two stiff flaps on the end of the epaulet. The straps are tacked together with break cord. The retracting strap pulls directly on these tacks and easily breaks them during deployment. Despite its success, this new design cannot accommodate pencils or pens in the flight jacket sleeve pocket, because the retracting strap could catch on them. The sleeve pocket must be moved to a new location, possibly the lower front torso.

The lower arm support strap is also a modification to the B-1 net/epaulet system. Its deployment lanyard uses the motion of the net ring to effect its deployment. Figure 55 shows an exploded view of the deployment of the four principal subsystems of the net/epaulet system. The net ring is shown as a component that is common to the four principal subsystems.

The net/epaulet system deployment required 60 inches of retraction strap travel. In the B-1 application, this is accomplished over 30 inches of seat travel up the rails using a 2-to-1 strap takeup ratio. To accommodate vertical seat adjustment, strap takeup begins 6 inches above the full down seat position; therefore, deployment is complete 36 inches above the full down position.

Since the seat occupant is exposed to maximum windblast leads below this seat elevation in the F-15 and F-16 aircraft, the B-1 takeup technique would be inadequate for these aircraft. A 3-to-1 takeup ratio would reduce the required seat elevation to 26 inches, which might be marginally acceptable for the F-15. Successful application of the net/epaulet system to the F-16 would require the use of a powered retraction device to achieve at least partial deployment before seat motion begins. This is an important design-to-cost consideration for the net/epaulet system.

<u>Windblast</u>

It was found during the B-1 sled test program that the epaulet was susceptable to being blown about in the cockpit drafts. However, no deployment failure was directly connected with this event. The stiff spring wand, the wand deploying lanyard, and the solid geometry of the retracting straps during deployment should combine to make the passage of the net and retracting strap outboard of the elbow insensitive to cockpit drafts.

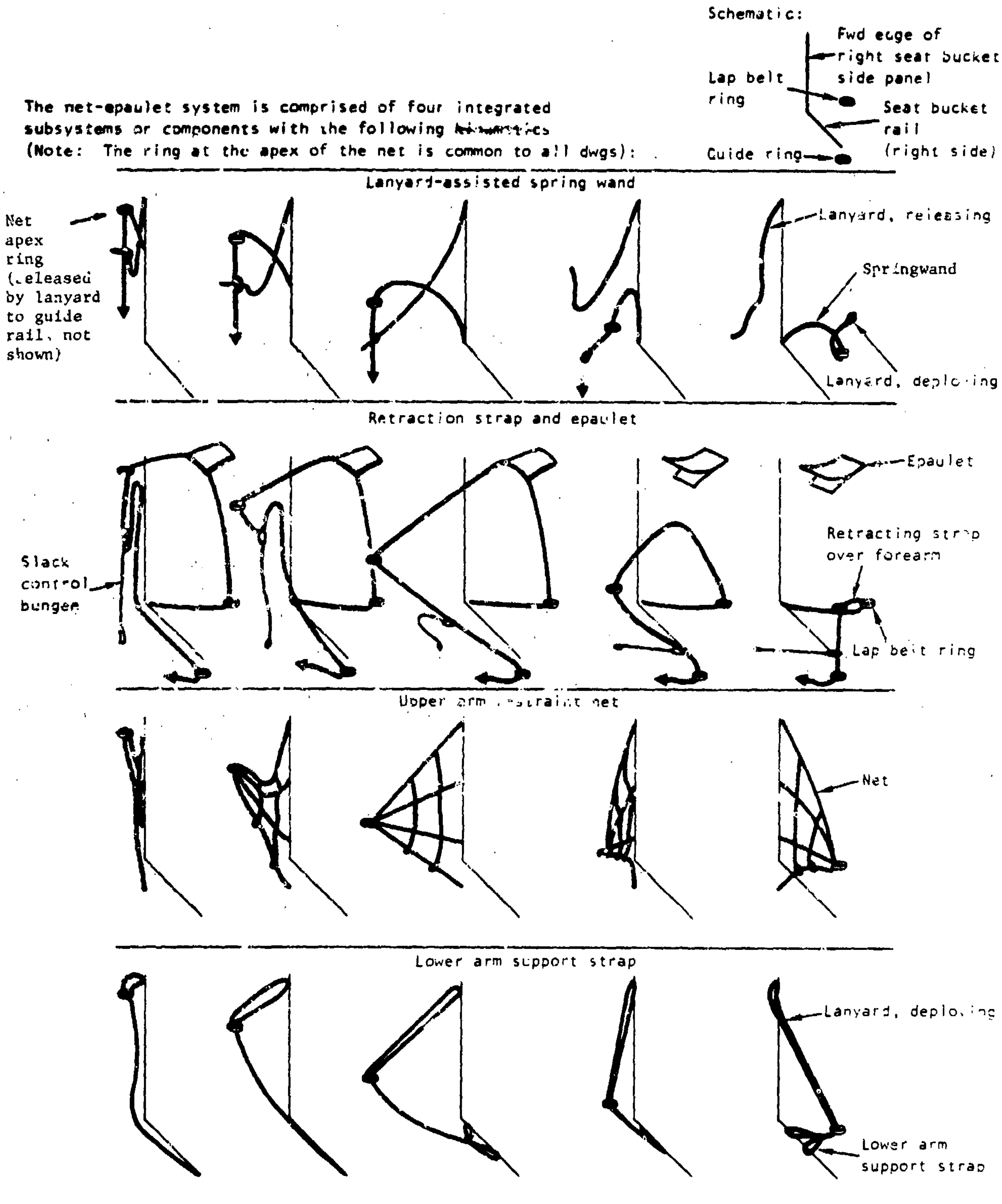

Figure 55. Net-Epaulet Kinematics

Seat-Man Separation

The following seat-man separation failure mode was revealed by the separation tests. As seat-man separation begins, the parachute pulls hard on the occupant's integrated harness and the survival kit via the survival kit straps. The seat occupant normally grips the ejection initiator handle(s). The shoulder retraction straps, lap belt, and seat pan are released, allowing the seat to rotate away from the decelerating occupant. Because of the occupant's pull on the initiator handles, the seat pan does not slip out from between the occupant and survival kit until the seat has rotated far enough to begin heavily loading the initiator handles with its inertial mass. In the meantime, the ends of the retracting straps, which were released with the lap belt anchors, are pulled underneath the forearms toward the rings near the lap belt buckle. From the lap belt rings, the straps run over the forearms to the net rings on either side. As the seat rotates away, the occupant's grip on the side-arm initiators pulls his forearms along the outside of the thighs and hips. At the same time, the retracting strap pushes the forearm against the hip area. The released ends of the retracting strap are pressed between the forearm and the body, causing a large amount of friction. If restraint release were stopped by this failure mode, the seat would be decelerated by the main parachute. The seat deceleration loads would be carried through the forearms and thighs to the leg straps of the integrated harness.

One such failure with a dummy occupant was captured on slow motion film. A film also was made of an attempt to repeat the conditions of the failure, but the attempt was not successful. Proper resolution of this failure mode requires studies with human subjects, wherein the subject is wearing a harness and sitting in ACES-II seat with connections to the survival kit made, initiator handles grasped, and arm restraints deployed and cinched. The subject should then be lifted a short distance off the ground, and the restraint release should be actuated. The release of the arm-restraint straps should then be carefully observed.

Torso Positioning

The windblast protection afforded by the net/epaulet concept is insensitive to torso position and would not interfere with repositioning of the torso after deployment.

Mobilty

The net/epaulet design restricts baseline, post-ejection mobility in the primary restraints at the shoulders and indirectly through the lap belt. The top radial strand of the net passes outside of the shoulder, near the joint. Under lateral loading of the seat, such as drogue-shock on a yawed seat, the inertial mass of the torso will push the shoulder against this part of the net. The design strategy of the net requires that this strand be taut; therefore, the undersirable loading of the shoulder joint is unavoidable. Nevertheless, the condition may be tolerable, because the remainder of the arm is well restrained, and the expected forces against the shoulder would be in toward the torso; therefore, only a fraction should actually be carried by the joint ligaments.

The cinching of the retracting straps against the belt rings acts to partially tighten the belt. Lateral loads on the belt will be carried through the opposite side arm strap. The strap will respond by moving through the belt ring, increasing the loads on the wrist and forearm of the arm opposite the lap belt load. The evaluation of these new arm loads found that although the wrist could be bent against the ejection handle, no injury was likely to result, because the geometry of the net results in its taking up most of the load rather than the forearm (Figure 36).

Ground Egress

None of the potential seat-man separation jamming modes for retracting strap release from the lap belt rings are present in the emergency ground egress situation. This is due to different routing of the straps (i.e., up to the shoulder instead of pressing the forearm against the released end of the strap). (Compare Figures 33 and 36.) Once the restraint emergency release handle has been pulled and the risers released, there are two options for egress:

1. Egress without regard for the retracting straps or lap belt.
2. Manually pull at the lap belt or either of the retracting straps, or both, to effect release of the strap from the belt ring prior to egress.

Under the first option, the lap belt will stay on the lap as the occupant steps over the canopy rail. Regardless of which direction the seat occupant turns, forward or aft, the straps will have a small potential for jamming on the belt ring. However, two emergency egress tests using the net/epaulet system (refer to Figures 52 and 53) did not produce any strap release jamming problems. Under the second option, the belt and straps are manually shed before the occupant moves to a crouch on the seat pan. Egress would then be equivalent to the baseline case.

Access To Restraint Emergency Release

The net/epaulet design provides access to the restraint release handle. The top strand of the net is sized in length to hold the net ring above the top of the forearm. Therefore, the occupant may withdraw his arm from under the deployed retracting strap by lifting the shoulder girdle and pulling the elbow back. Once the arm is out, the restraint release handle can be accessed and operated.

Encumbrance

During normal use, the net/epaulet system requires two retracting straps to be worn, one over each shoulder. Epaulet-type keepers attached to the parachute risers on the shoulder hold the straps in position. From the keepers, the two straps run down across the chest to the lap belt buckle. This strap configuration has been flown in the B-1 prototype 4 flight-test program for one year and is accepted by the flight-test crewmembers. The introduction of the retraction-strap slack control technique, which keeps the straps snug against the chest during all kinds of body movements by the seat occupant, was essential in winning crew acceptance of the design.

After donning, the system is neat in appearance and unencumbering. The system does not restrict external or internal visual access. The positioning of the net storage channels on the sides of the seat back restricts the space available for movements of the elbow in that area and therefore interferes with reach access to the side consoles. This will have a greater negative impact on fighter flight crews than on the B-1 crewmembers, because the relatively large panel area of the B-1 minimizes side-console access criticality. In any case, the B-1 situation is extreme, because the storage channels must stand off 2 inches from the seat back sides to accommodate the B-1 armrests. The visual impact of the net/epaulet system prior to ingress is poor. The system is complex. This will be especially noticed in comparison to the present plain appearance of the F-15 and F-16 ACES-II installations.

Donning/Doffing

Donning exploits the existing ingress procedures for connecting the parachute risers and lap belt. The epaulets are automatically positioned when the risers are connected to the harness. The straps hanging from the fronts of the epaulets are pulled over the arms, and then the lap belt is buckled. This completes arm-restraint donning, and no new connections are required. The presence of the retraction straps at the lap belt complicates the belt buckling task, since care must be taken to visually inspect the retraction strap routing to ensure that no tangles exist. This situation would be improved if the belt adjusters were moved to the anchor ends of the belt halves.

D-Ring and Side-Arm Compatibility

The net/epaulet system provides equal protection to occupants of D-ring or side-arm ejection initiator handle equipped seats. In both cases, the retracting straps are drawn down over the forearms, aiding the occupant in retaining his grip on the handles, while the nets provide lateral restraint. However, the D-ring equipped seat will have a negative impact on net/epaulet performance during seat-man separation because, if the grip is intact, the forearms will be drawn down over the lap belt rings. The result could be temporary seat-man separation failure and a possible injury risk for the arms or legs.

WINDBLAST PROTECTION SYSTEM SELECTION

Designers may perceive a comprehensive man-centered design evaluation plan as expensive and complex. Such a perception can act as strong disincentive to investigate man-centered windblast protection problems beyond the narrow bounds of the quantitative design criteria currently available. A major goal of this program was to demonstrate the feasibility and utility of conducting low-cost, qualitative, yet comprehensive investigations of man-centered escape design problems using inexpensive test fixtures and qualitative design performance criteria, test data and scoring techniques. The test fixtures, performance criteria, and test data were presented in the preceding sections. This section covers the use of qualitative scoring techniques.

The method selected for scoring the qualitative evaluation data is illustrated by Table 4. In this table, each of the 11 performance evaluation areas is assigned a subjective performance scale. That portion of the scale lying between the worst and best performances by the field of candidate windblast protection designs, including the baseline ACES-II seat, is shown. The scales are normalized by equating the best and worst performers across the eleven evaluation areas. The advantages of this graphic technique are as follows:

1. An evaluator's judgement regarding the relative advantages and disadvantages between candidate designs can be expressed in a quasi-quantitative form, which is much more efficient than a written descriptive expression, particularly when based on qualitative evaluation data.

2. The act of deciding what relative position a candidate design should take on a specific performance scale can stimulate the evaluator to consider the cumulative effect of multiple design features which determine the design performance in that specific requirement area. Written expression of such cumulative effects is awkward and difficult and can act as a disincentive to their consideration, while expression on a relative scale is fast and flexible and can act as a stimulant.

3. The efficiency, flexibility, and information density of a graphic expression facilitates truly comprehensive coverage of man-centered problem areas in windblast protection designs.

4. The inclusion of the baseline windblast protection designs; e.g., special hand grips, lateral leg fences, etc., with the new protection devices:

   a. Provides for comparison to the status quo.
   b. Provides a sense of direction to each performance scale (i.e., in some the baseline is good and in others, the baseline is bad).

5. Critical areas of device performance may be located and studied by visual inspection of the patterns formed by the completed chart. This makes it very useful for communicating the conclusions of a complicated evaluation program to other evaluators, reviewers, and administrators.

TABLE 4. PERFORMANCE SCORES FOR FIVE ARM WINDBLAST PROTECTION CONCEPTS

Evaluation areas	Worst ← Performance → Best
1. Biomechanical loads	B — D — N — S — A
2. Deployment	D — N — S — A — B
3. Windblast	B — D — N — S — A
4. Seat-man separation	N — S — D — A — B
5. Torso positioning	D — S — N — A — B
5. Mobility	N — D — S — A — B
7. Ground egress	A — D — S — N — B
8. Access to RER*	D — S — A — N — B
9. Encumberance	D — A — S N — B
10. Donning/doffing	D — A — S N — B
11. D-ring vs side-arm	B — D — S — A — N

N - net/epaulet (No. 6) D - deploying sleeve (No. 2)

S - sleeve (No. 5) A - arm straps (No. 1)

B - baseline ACES II * - Restraint Emergency Release

An important caution in regard to interpreting the results of a performance scoring system like the one shown in Table 4 has to do with the fact that the results pertain to a fixed set of competing design concepts. If a design which had been scored best or worst in at least one evaluation area were removed from the set, the other scores in that evaluation area would have to be adjusted in relation to the new best or worst design. A similar caution would be appropriate if the number of concepts in the set were to be increased.

Table 4 shows that of the five windblast protection designs studied by this program, there is not one which performs consistently near the best across the performance categories. The net/epaulet design comes closest to this consistency, with the exception of its seat-man separation failure mode and mobility performance. The net/epaulet performance score on seat-man separation would improve if a retracting strap cutter operated at restraint release were added to the design. The lower score on the mobility evaluation is not critical. Therefore, the net/epaulet system is selected as the one with the best man-centered design. The arm-length sleeve concept could compete with the net/epaulet concept if the deployment cord pull point was moved from the forward seat bucket side to between the occupant's legs on the forward edge of the seat-pan. Because two connections would be required, donning/doffing performance would be worse, but the change would improve performance on:

1. Deployment - the amount of deployment cord movement required would be reduced from 54 to 20 inches, which would give full deployment after 10 inches of seat travel at a two-to-one takeup ratio.

2. Windblast - the faster deployment would mean a shorter exposure to windblast and the between-the-legs pull point is better for retracting out of position limbs.

3. Mobility - the load path running from the seat-pan pull point under the shoulder to the shoulder ring would provide direct lateral support to the torso.

4. Ground Egress - the release sheath over the deployment cord will require less slack and, therefore, will release earlier, and the pull angle will be more orthogonal to the arm so that the sleeve will not be pulled down the arm by the release breakout force.

5. D-ring Compatibility - the sleeve will now support the forearm while it is in the D-ring gripping configuration.

Sleeve performance in the area of access to the restraint emergency release handle could be improved by addition of a releasable latch on the sleeve strap loop near the wrist opening. The occupant could reach and operate such a latch to release the right sleeve. After such release, access to the restraint release handle would be close to the baseline access.

The sleeve has some other advantages over the net/epaulet system, including: (1) simpler design, (2) lower cost, (3) greater reliability and maintainability, (4) will capture the arm in any position, and (5) less impact to seat space envelope. Because of these advantages and the sleeve potential for performance improvements through minor design changes, the sleeve concept is selected as a promising alternative to net/epaulet system.

Table 5 presents a compatative summary of leg protection device performances. The competing devices were the baseline ACES-II, G-suit modification, and leg-strap system. The G-suit performs better than the leg straps in the categories of:

1. Deployment - the G-suit need not capture a leg, but needs merely to retract it to the seat; also seat motion may be used.

2. Windblast - the retracting straps are under the legs and, therefore, sheltered from the windblast; there are no difficult deployment kinematics.

3. Torso Positioning - the retracting straps are under the legs and are unaffected by torso position.

4. Mobility - the G-suit gives leg restraint without fixing the leg to the seat.

5. Encumbrance - the G-suit is a familiar piece of equipment, and the retracting straps are out of view and out of the way.

6. D-ring versus Side-arm Compatibility - the position of the arms has no adverse impact on any G-suit restraint performance.

These areas of better performance by the G-suit design outweigh the advantages held by the leg straps in seat-man separation and donning/doffing. Therefore, the G-suit modification is selected as having the best overall man-centered performance of the leg windblast protection designs.

TABLE 5. PERFORMANCE SCORES FOR THREE LEG WINDBLAST PROTECTION CONCEPTS

Evaluation areas	Worst ← Performance → Best
1. Biomechanical loads	B — L — G
2. Deployment	L — G — B
3. Windblast	B — L — G
4. Seat-man separation	G — L — B
5. Torso positioning	L — G — B
6. Mobility	L — G — B
7. Ground egress	L — G — B
8. Access to RER	L — G — B
9. Encumbrance	L — G — B
10. Donning/doffing	G — L — B
11. D-ring vs side-arm	L — G — B

B - baseline ACES-II

G - G-suit modification

L - leg straps

Appendix A

GENERAL TEST PLAN/PROCEDURES

INTRODUCTION

This is a proposed general test plan/procedure for testing arm and leg windblast protection device concepts for the ACES-II seat. The plan specifies the design and fabrication or acquisition of several test fixtures to be used to support test articles in or on test facilities such as wind tunnels and impact sleds. The scope of the plan expands in incremented steps toward higher fidelity and more expensive testing. This was done so that the level of testing can be tailored to the level of funding available for this project without sacrificing comprehensiveness.

The design and fabrication of the fixtures will be accomplished in parallel with the final engineering development of the windblast protection concepts.

The remainder of the plan is divided into three sections, one describing the goals and objectives of the plan; another describing the specified tests and evaluations which form the body of the plan; and a third describing the test articles, fixtures, and facilities required to support the test plan program.

Table A-1 relates the goals, test descriptions, and required hardware in matrix form.

GOALS AND OBJECTIVES OF FOLLOW-ON PROGRAM

FUNCTIONAL PERFORMANCE DEMONSTRATION

The capability of the protection devices to function, according to their intended purposes, will be demonstrated. In particular, it will be demonstrated for each device that it is capable of functioning properly under conditions reasonably expected under emergency ejection conditions.

Toward this objective, each device will be tested as indicated in Table A-1 under "Function".

PROOF AND ULTIMATE STRENGTHS

The windblast protection devices will each be tested for proof and ultimate strength in stress tests which will be directly related to the forces which the devices must bear in order to provide protection against injury during ejection and recovery.

COMPATIBILITY WITH FLIGHT CREW MISSION

The compatibility of each device with the aircrew mission will be demonstrated. All aspects of normal and emergency crew operations will be included in the demonstrations.

Therefore, each device will be tested as indicated in Table A-1 under "Crew Compatibility".

TABLE A-1. VERIFICATION TEST PLAN

Tests & Evaluations	Goals And Objectives: Function	Strength	Crew Compatibility	Aircraft Compatibility	Escape System Compatibility	Logistics	Test Articles, Fixtures, And Facilities: Arm Devices	Leg Devices	ACES Seat: F-15 & F-16	Wind Tunnel Fixture	Separation Test Fixture	Drogue Shock Test Fixture	Sled Wind Blast Fixture	Forebody Sleds F-15 & F-16	Stress Lab Fixture	Catapult Tower Facility	Wind Tunnel Facility	Impact Sled Facility	Sled Track Facility	Simulators	Flight Test
Catapult Tower Test	o				o		o	o	o							o					
Wind Tunnel Tests	o				o		o	o	o	o							o				
Seat-Man Sep Impact Sled Tests	o				o		o	o	o		o							o			
Drogue-Shock, Impact Sled Tests	o	o					o	o	o			o						o			
Powered Deployment Tests	o				o		o	o	o												
Sled Windblast Tests	o	o					o	o	o				o						o		
Sled Ejection Tests	o	o					o	o	o					o					o		
ASD Evaluation Tests			o		o		o	o	o											o	
Anthropometric Evaluation			o				o	o	o											o	
Simulator Evaluations: F-15 &-16	o		o	o			o	o	o											o	
Flight-Test Eval: F-15 &-16	o		o				o	o	o												o
Ground Crew Eval: F-15 &-16				o		o	o	o	o											o	o
Seat Manufacturer Evaluations					o		o	o	o												
Logistics Command Evaluations						o	o	o	o												
Aircraft Using Command Eval				o	o		o	o	o											o	o

COMPATIBILITY WITH AIRCRAFT MISSION

The compatibility of each device with the aircraft mission will be demonstrated. Special consideration will be given to decrements in mission performance to be expected as a result of the added weight and bulk of the device. In addition, it will be demonstrated that the devices are insensitive to the climatic and environmental variations characteristics of the host aircraft field of operations.

COMPATIBILITY WITH ACES-II EJECTION SEAT

Each device will be shown to be compatible with the proper functioning of the ACES-II ejection seat. This compatibility will be demonstrated for all phases of seat functioning.

Toward this objective, each device will be tested as indicated in Table A-1 under "Escape system compatibility".

LOGISTICS BURDEN

The protection devices will be shown to present the least possible logistics burden compatible with their intended function. This demonstration will include descriptions of estimated life cycles and the maintenance burdens.

Toward this objective, each device will be tested and evaluated as indicated in Table A-1 under "Logistics".

TESTS AND EVALUATIONS

CATAPULT TOWER TESTS

The Naval Air Development Center Ejection Tower facility will be used to conduct catapult tests of each device. Devices which employ powered deployment or retraction will have that function integrated into the catapult tower tests. If any device employs breakaway links to provide restraint tensioning, its test will be instrumented to provide data on pull force versus catapult stroke displacement, and these data will be analyzed for potential effects on spinal injury. Slow motion photography will be used to record the functioning of the devices during their tests. Measurements will be made of seat pan force, seat acceleration, body segment displacements and accelerations, and retraint loads. After consecutive successful dummy tests, tests with human subjects will be conducted.

WIND TUNNEL TESTS

A wind tunnel facility will be used to conduct full-scale tests of the protection devices. Low-speed tests will be conducted with human subjects to obtain direct reports of the quality of the support of the devices against windblast forces. The test articles will be oriented in four pitch and four yaw positions and four combined pitch-yaw positions for a total of 12 runs per device. Aerodynamic forces on the seat will be recorded during the tests. These data will be compared with data from a test in which a seat without protection devices was used in order to determine the effect, if any, of the devices on the aerodynamic

stability of the seat. If aerodynamic analysis of preliminary tests indicate insignificant effect on the aerodynamic stability of the seat, these low-speed tests may be reduced in scope or eliminated completely.

A wind tunnel facility will be used to conduct high-speed wind tunnel tests on each device. These tests will use anthropometric dummies in place of human subjects. The tests will provide data on device performance in high-Q environments. The seat will be positioned in five pitch attitudes and three yaw attitudes, for a total of eight runs per device. The attachments of the device to the seat will be instrumented with force transducers. These force data shall be combined with geometry data from metric cameras to support an analysis of the loads in the joints of the arms and legs. Deployment insensitivity to windblast during separation from the aircraft will be demonstrated by deployments within a forebody simulator in a windblast facility such as the Dayton T. Brown facility.

SEAT-MAN SEPARATION IMPACT SLED TESTS

A two-phase testing approach will be used. The first phase will employ the motion of a flat-bed truck and the spring force of a large shock cord to simulate the force dynamics of parachute opening shock. If performance in these tests is satisfactory, then phase II testing using the AFAMRL Impact sled test facility will be conducted.

The tests will simulate the forces and relative velocities which characterize high-speed extraction of the occupant from the seat at main parachute inflation. The primary instrumentation would measure the forces required to achieve release of the arm or leg restraint devices. The tests could serve a double purpose by collecting data on devices which might protect the occupant from the hazards of extraction from a yawed seat.

DROGUE SHOCK IMPACT TESTS

The AFAMRL impact test facility will be used to conduct tests of device performance during simulated drogue-inflation-induced rapid realignment of the seat and its occupant. Either decelerating or accelerating impact facilities can be used. Prior to test, the seat will be aligned in a predetermined attitude relative to the impact sled. During the velocity change, the seat will be realigned by a simulated drogue bridle attached to the sled. The tests can provide additional data on devices intended to improve the occupant's tolerance to lateral acceleration loads and high angular accelerations.

The primary instrumentation for these tests will be metric slow motion photography. Additional instrumentation will measure drogue bridle loads for comparison with ejection test data and restraint loads, where possible.

These tests require a fixture to hold the seat before, during, and after testing.

POWERED DEPLOYMENT TESTS

A contractor-supplied powered deployment simulator will be used to conduct tests of the performance of the device during deployment from the normal state to the protection state. Only devices which are to employ precatapult deployment must run through this test. The tests will include runs which establish the sensitivities of the device to abnormal positions of the limbs and torso, and to simultaneous torso retraction. Primary instrumentation will measure the actuation loads during deployment and loads on selected hardware. Secondary instrumentation will be metric slow motion photography.

SLED WINDBLAST TESTS

A rocket sled track facility will be used to conduct tests of the performance of the device at maximum dynamic pressure. These tests will simulate dynamic pressure conditions during the rocket-powered seat-aircraft separation phase of the ejection. The primary instrumentation will measure loads on the protection devices and will be located to provide data which will support determination of the loads on the occupant's joints. Metric slow motion photography will record the presence of flutter, if any, in the occupant's limbs.

These tests will require a fixture to support the seat on the sled during the test.

SLED EJECTION TESTS

Due to the extreme expense of complete ejection tests, these tests will be integrated into a future escape system verification test program.

AERONAUTICAL SYSTEMS DIVISION EVALUATIONS

An evaluation of the performance of the device will be made by personnel from the ASD Engineering staff at Wright Patterson AFB. This evaluation will, on the basis of test results and inspections, confirm the ability of the device to protect against windblast injury while satisfying the various constraints on its design.

ANTHROPOMETRIC EVALUATIONS

The devices will be evaluated for sensitivity to the extremes of standard anthropometric measurements. The appropriateness of the size ranges, if any, will be evaluated. Human subjects representing anthropometric extremes will be employed in demonstrations of device performance in the stowed and protection states. The contractor will conduct these evaluations.

SIMULATOR EVALUATIONS

The cockpit simulators for the F-15 and F-16 aircraft will be equiped with the devices. Simulator users will be interviewed regarding the impact of the devices on the pilot's workload, comfort, mobility, visual access, and other aspects of piloting missions.

FLIGHT-TEST EVALUATIONS - F-15 AND F-16

After appropriate reviews and approvals, the devices will be installed on F-15 and F-16 flight-test aircraft for evaluation by the flight-test pilots in the actual aircraft environment. Flight-test aircraft of these types are operating at Edwards AFB, California.

GROUND CREW EVALUATIONS

The crew chiefs of the flight-test aircraft will be interviewed regarding the performance of the devices with respect to the ground maintenance and operations task required by the aircraft systems.

SEAT MANUFACTURER EVALUATIONS

The seat manufacturer will be consulted regarding the stress loads imposed on the seat structure by the various devices. The manufacturer will be asked to evaluate the effect of the devices on the intended performance of the seat.

LOGISTICS COMMAND EVALUATIONS

The Air Force agency responsible for logistics effectiveness will be given all available data on each device and then asked to evaluate the probable burden of each device on the logistics system.

AIRCRAFT USING COMMAND EVALUATIONS

The potential using commands for the windblast protection devices will be contacted for the purpose of identifying an office within each command which will accept summary briefing letters on the progress of the testing program and relay suggestions, comments, criticisms, and any other information from pilots in the field regarding the eventual deployment of the devices in the force.

TEST ARTICLES, FIXTURES, AND FACILITIES

ARM PROTECTION DEVICES

At present, the two prime candidates for arm protection devices are (1) an arm length sleeve which is donned during ingress to the seat and (2) an actively deployed net and lower arm strap system based on the design developed for the B-1 model of the ACES-II seat. Other candidate device designs which have successfully passed design requirement evaluations and are available in testable prototypes will be included in the test program.

LEG PROTECTION DEVICES

The current candidate for leg restraint is a modified anti-G garment. Other acceptable leg restraint devices should also be included in the test program.

ACES-II SEAT - F-15 AND F-16 MODELS

The F-15 seat has side arm ejection initiation handles. The F-16 seat, because of its side console location for flight control, has a center-pull D-ring ejection initiation handle.

WIND TUNNEL FIXTURE

The test program may either design and fabricate a seat support fixture for wind tunnel testing or adapt an existing support fixture.

SEPARATION TEST FIXTURE

This fixture will support the seat prior to the sled velocity change and subsequently transmit the simulated parachute opening shock from the sled to the parachute risers of the dummy. A new fixture may be built, or an existing fixture may be adapted to this program.

DROGUE SHOCK TEST FIXTURE

This fixture will support the seat prior to the sled velocity change and subsequently transmit the simulated drogue opening shock to the drogue bridle from the sled. The separation test fixture will also serve as the drogue shock test fixture.

SLED WINDBLAST FIXTURE

This fixture will support the seat on the sled during the captive windblast tests. The fixture will either be built or adapted from an existing fixture.

FOREBODY SLEDS

Forebody sleds for the F-15 and F-16 will be used as platforms for the seat ejection tests. Existing sleds from the F-15 and F-16 escape system verification test programs will be adapted for this program.

STRESS LAB FIXTURE

This fixture will hold the seat during device load tests and will also provide reaction points, for the force applicators used in these tests.

CATAPULT TOWER FACILITY

This facility will be used to conduct catapult tower tests. The facility will be the NADC Ejection Tower.

WIND TUNNEL TEST FACILITY

This facility will be used to conduct low-speed windblast tests of the protection devices. The facility for this test will be the University of Maryland wind tunnel or similar facility.

IMPACT SLED FACILITY

This facility will be used to conduct the seat-man separation and drogue shock tests. The facility will be the AFAMRL impact test sled.

SIMULATORS - FLIGHT AND INSTRUMENT

These facilities will be used to conduct the evaluations of device sensitivity to anthropometry, impact on crew tasks, and general safety. The simulators are to be indentified by the Air Force.

REFERENCES

Auffet, R., R. P. Delahaye, February 1975, "Spinal Injury After Ejection", in AGARD-AR-72, NATO Advisory Group for Aerospace Research and Development.

Belk, W. F., 1980, "Limb Flail Injuries and the Effect of Extremity Restraints in USAF Ejections (1971-1978)", in SAFE Journal, Vol. 10, No. 2.

Cummings, R. J., F. E. Dasata, June 1979, Exploratory Development of Aircrew Windblast Protection Concepts, AMRL-TR-79-16, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, (AD A072013)

Every, M. G., J. F. Parker, March 1976, Biomedical Aspects of Aircraft Escape and Survival Under Combat Conditions, Office of Naval Research, Contact No. N00014-72-C-0101, AO A021 921.

Fryer, D. I., July 1961, The Effects Upon Man of Exposure to High Pressure Loads, Report No. FPRC/1167, Air Ministry (England), Flying Personnel Research Committee.

Grood, E., F. Noyes, D. Butler, October 1978, Knee Flail Design Limits: Background, Experimentation, and Design Criteria, AMRL-TR-78-58, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, (AD A062384)

Hawker, F. W., A. J. Euler, July 1975, Extended Measurements of Aerodynamic Stability and Limb Dislodgement Forces with the ACES-II Ejection Seat, AMRL-TR-75-15, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, (AD A014432)

Hawker, F. W., A. J. Euler, June 1976, Wind Tunnel Measurements of Vertical Acting Limb Flail Forces and Torso/Seat Back Forces in an ACES-II Ejection Seat, AMRL-TR-76-3, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, (AD A029180)

Horner, T. W., F. W. Hawker, May 1973, A Statistical Study of Grip Retention Force, AMRL-TR-72-110, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, (AD 767904)

NATO/AGARD, July 1975, Biodynamic Response to Windblast, AGARD-CP-170, Advisory Group for Aerospace Research and Development of the North Atlantic Treaty Organization.

Newhouse, H. L., P. R. Payne, J. P. Brown, December 1980, Wind Tunnel Measurements of Total Force and Extremity Flail Potential Forces on a Crew Member in Close Proximity to a Cockpit, AMRL-TR-79-110, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio , (AD A100917)

Payne, P. R., May 1974, On the Avoidance of Limb Flail Injury by Ejection Seat Stabilization, AMRL-TR-74-9, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio , (AD 783913)

Payne, P. R., December 1974, Some Studies Relating to "Limb Flailing" After an Emergency Escape From an Aircraft, AMRL-TR-73-24, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio , (AD A005699)

Payne, P. R., F. W. Hawker, A. J. Euler, July 1975, Stability and Limb Dislodgement Force Measurements with the F-105 and ACES-II Ejection Seats AMRL-TR-75-8, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. (AD A015726)

Phillips, N. R. Carr, T. Wittmann, R. Scranton, December 1973, An Investigation of Automatic Restraint and Body Positioning Techniques, AMRL-TR-71-101, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, (AD 773857)

Stencel Aero Engineering Corps., May 1979, Prototype Development: Passive, Seat-Mounted, Limb Retention System, NADC-79-201-60, Naval Air Development Center, Pennsylvania.

☆U.S.Government Printing Office: 1982 — 559-007/6030